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Control of urban runoff through the use of permeable pavements

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CONTROL OF URBAN RUNOFF THROUGH THE USE OF PERMEABLE PAVEMENTS

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A permeable pavement car park surface

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Abstract

In order to control stormwater runoff, engineers and hydrologists have used various techniques to attempt to reduce or delay the volume of water which reaches the sewer system. Recently, international approaches have favoured the idea of "source control" or "on-site" retention. This technique stores water in areas close to the point at which precipitation lands. Permeable pavements and similar stormwater control devices have not been exploited in the United Kingdom. Their adoption has been hindered by a lack of knowledge of their hydrological performance. This research aims to produce information on the hydrological performance of a car park surface and to produce a model which can predict the hydrological response to varying rainfall inputs.

The objective of this thesis is to examine the hydrological behaviour of a model car park surface under varying rainfall conditions. The study has involved the construction of full-scale permeable pavement model car park structures and a rainfall simulator for use in the laboratory. A monitoring procedure was developed in order to measure inputs and changes in drainage, storage and evaporation over short (less than 2 hours) and long (up to 3 months) time scales. A range of rainfall simulations were applied to the model car park surfaces which differed in intensity, duration and volume. Hydrological processes were monitored over an 18 month period. Results suggest that evaporation, discharge and retention in the structures were strongly influenced by the particle size of the bedding material and the surface blocks. In general an average of 55% of a 15 mm h^{-1} rainfall event could be retained by an initially dry structure. Subsequent simulations suggest that approximately 30% of a 15 mm h^{-1} rainfall event could be stored by an initially wet structure (with a minimum time interval of 72 hours).

Sediments were also applied to the car park structures in order to monitor the effects of clogging on hydrological performance and to quantify the ability of the structures to act as a primary screening site for sediments. The application of sediments to the structure showed that evaporation from the structure increased by as much as 25-30%. Laboratory simulation of clogging effects was also compared to data gathered from field sites and the results suggested that laboratory simulations provided a good approximation of the migration of sediments in the structure.

A model of the hydrological performance of the structure has been developed to be used as a predictive tool. The model relates rainfall inputs to water retention and discharge output over consecutive rainfall events. It also allows evaporation and long-term retention by the structure to be estimated over differing lengths of dry periods. The model results indicate that discharge was predicted to an accuracy of 78% (based on a percentage difference between the observed and predicted values), and evaporation and retention were predicted to an accuracy of 80%.

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Chapter 1

1.1 Introduction

In order to control stormwater runoff, engineers and hydrologists have used various techniques to attempt to reduce or delay the volume of water which reaches the sewer system. Recently, international approaches have favoured the idea of "source control" or "on-site" retention (Pratt, 1995). This technique stores water in areas close to the point at which precipitation lands and has the advantage of reducing the volume of runoff in downstream rivers and sewers and of increasing potential groundwater recharge which feeds the base-flow in rivers.

The source control structure considered in this research project is a permeable pavement which allows rapid infiltration and on-site storage of precipitation. It's design allows water to pass between the specially designed surface blocks, where it is stored below the surface in layers of gravel and crushed stone. Any water stored (up to 100 mm of rainfall) can be removed, if required, to a grey water system (Schilling *et al.*, 1988), or released into a downstream sewer or water-course at a controlled rate and time. Stored water may also be allowed to infiltrate into the ground or evaporate.

The structure is designed to be used in areas of low traffic speed and density, for example in car parks. 122,000 cars are licensed in the city of Coventry alone and an estimated 1.5 million m^2 of land in the city is used for car parking purposes. With the city covering approximately 80 km^2, car parking surfaces cover approximately 2% of the city. This may seem a small percentage of the area, but it does not include residential roads or driveways where this technique may also be adopted. The structure has a high storage capacity and, as a result, the runoff from roof surfaces could be directed into the structure. If roof runoff was redirected, it is estimated that between 30 and 40% of a storm event with a return period of two years can be stored, in addition to the rainfall reaching the car park surface directly (CIRIA, 1992). This technique, therefore, has a large potential for adoption in limiting or controlling stormwater discharge from urban surfaces by creating on-site retention; thus reducing the risk of flooding and potentially reducing pollutant discharge.

The study has involved the construction of full-scale permeable pavement model car park structures in the laboratory. A range of rainfall simulations were applied to the model car park surfaces which differed in intensity, duration and volume. Hydrological processes were monitored over an 18 month period. Sediments were also applied to the car park structures in order to monitor the effects of clogging on hydrological performance and to quantify the ability of the structures to act as a primary screening site for sediments. Laboratory simulation of clogging was also compared to data gathered from field sites.

A model of the hydrological performance of the structure has been developed. The model relates rainfall inputs to water retention and discharge output over consecutive rainfall events. It also allows evaporation and long-term retention by the structure to be estimated over differing lengths of dry periods.

1.2 Overview of Thesis

An overview of the thesis is given in Figure 1.1 and the following paragraphs provide a brief summary of each chapter.

Chapter 2 - Literature Review

A complete review of the literature covering urban hydrology and urban stormwater control would be extremely time-consuming. It is not the aim of this research project to undertake such a challenge but to provide a general introduction to some of the more important hydrological problems associated with urbanisation of direct relevance to the research project. Section 2.1 of the literature review provides a brief overview of these problems and suggests that the use of infiltration techniques may help to alleviate part of the detrimental impacts on receiving urban water courses. Section 2.2 outlines the changes in philosophy adopted by engineers and hydrologists in their approach to urban stormwater control since the 1960s. Section 2.3 discusses the traditional and modern techniques used to control stormwater runoff, which is followed in section 2.4, by a more detailed review of research on permeable pavements. Chapter 2 places this research in context by identifying the lack of hydrological performance details on permeable pavement structures.

Chapter 3 - Experimental Design

This chapter has been divided into three sections. After a brief introduction, Section 3.2 describes the development of equipment and instrumentation used in the laboratory experiments. The research project monitored water retention, discharge and evaporation

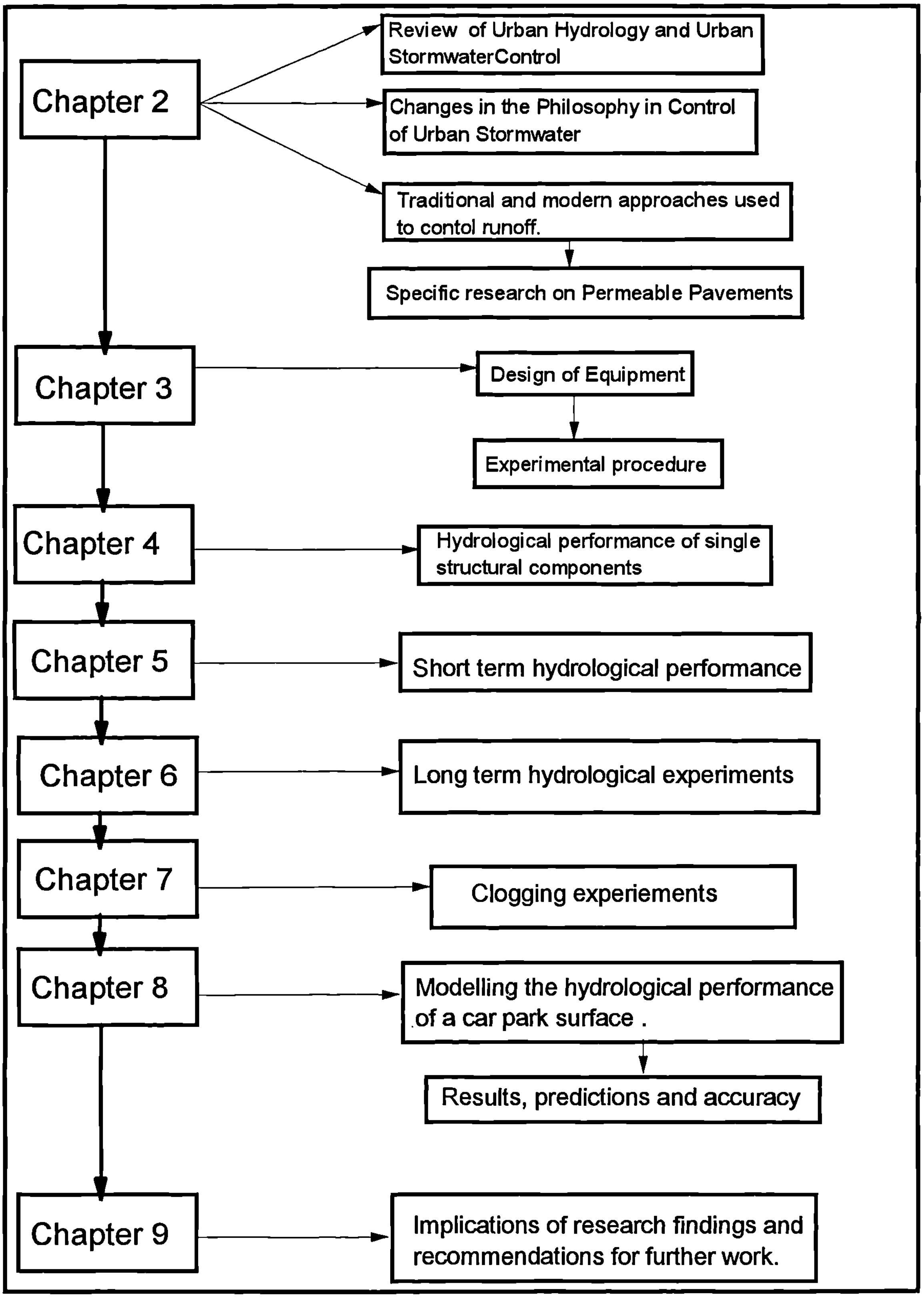


Figure 1.1 An overview of the structure of the thesis.

from the model car park structures. The equipment required to do this was specially designed and constructed for the purposes of this research project. Section 3.2 gives details on the model permeable pavement structures, weighing equipment and rainfall simulator design. Section 3.3 explains the experimental procedure for both the hydrological simulations and the clogging experiments. In total, 41 hydrological simulations and 12 clogging experiments are discussed in this thesis.

Chapter 4 - Hydrological characteristics of concrete blocks and bedding material.
The data produced during experimentation has been divided into four chapters (Chapters 4 to 7). Chapter 4 presents and discusses the hydrological performance of the individual structural components. It is important to appreciate how the individual components perform before attempting to understand the performance of the composite large-scale structures. Chapter 4 examines the retention and evaporation performance of individual structural components and compares the individual component performance with box experiments containing similar components.

Chapter 5 - Short-term hydrological experiements.
Short-term hydrological performance (up to 2 hours following the end of a rainfall simulation) of the model car park structure is examined in Chapter 5. Rainfall, retention and discharge characteristics are examined to ascertain the influence of rainfall characteristics and box components on the overall performance. Analysis of hydrograph response to storm hyetograms is also discussed.

Chapter 6 - Long-term behaviour of the structure.

This chapter examines the long-term hydrological performance of the model car park structure with regard to retention and evaporation processes after the cessation of rainfall and drainage. Model box experimental results are also compared to evaporation pan data in order to assess the importance of water availability on the evaporation process. The influence of the structural components on retention and evaporation is also examined.

Chapter 7 - Clogging experiements.

The effect of clogging on the hydrological performance of the model car park is discussed in this chapter. Laboratory simulations of particulate additions are examined in relation to their effects on: infiltration; the lifespan of the structure; the migration of particulate material; and on the overall hydrological performance of the structure. Information from field sites is also analysed.

Chapter 8 - Modelling the hydrological performance of the car park surface.

The model that has been produced to predict the hydrological performance of the car park structure is discussed in Chapter 8. From the results presented in Chapters 4 to 7, it was possible to identify patterns in retention and evaporation from the varying bedding materials and surface blocks (structural components). The performance of the structural components were predictable by simple mathematical equations. A computer model was developed to predict the hydrological performance of full-scale car park structures using information on the hydrological performance of the single components discussed in Chapters 4 to 7. The model predicts retention, discharge and evaporation and these predictions were compared with results from the hydrological simulations in order to assess the performance of the model and it's accuracy as a predictive tool.

Chapter 9 - Conclusions.

This chapter discusses the implications of the results obtained during experimentation and suggests specific design criteria which may enhance the performance of the car park structure. A consideration is also made of how urban stormwater runoff could be controlled by the use of permeable pavements.

Permeable pavements and similar stormwater control devices have not been exploited in the United Kingdom. Their adoption has been hindered by a lack of knowledge of their hydrological performance. This research aims to produce information on the hydrological performance of a car park surface and to produce a model which can predict the hydrological response to varying rainfall inputs. Projects similar to the one presented in this thesis should be encouraged, in order to allow for a wider understanding and application of "on-site" techniques to control urban stormwater runoff.

Chapter 2 - Literature Review.

This chapter reviews literature on the hydrological problems associated with urbanisation which has direct relevance to the research project.

2.1 Urban Hydrology and Urban Storm Water Control.

Urbanisation can drastically influence the environment and it's hydrological regime. As most countries develop, the percentage of impermeable area increases due to expansion of industrial activities, development of residential areas and the necessary infrastructure for transport. This occurs to the detriment of rural areas. Pearce (1993) reported the findings of a recent investigation by the Institute of Terrestrial and Fresh Water Ecology which showed that in England and Wales, between 1984 and 1990, 130 km^2 per annum was lost from the countryside as a result of urbanisation. Over the same time period there was a 40% increase in "hard areas without buildings", for example car parks, demolished factory sites and airfields.

The impact of an increase in impermeable surfaces is generally twofold:

1) impacts associated with water quantity in the hydrological cycle;
2) impacts associated with water quality.

2.1.1 Modifications to the hydrological cycle.

Impermeable surfaces disrupt a large proportion of the natural hydrological cycle, particularly by inhibiting infiltration and the subsequent percolation of excess storm waters (see Figure 2.1) (Diniz, 1978; UNESCO, 1975). This often creates a large proportion of rapid overland flow since rainfall intensity exceeds infiltration capacity in the classical Hortonian sense (Horton, 1933).

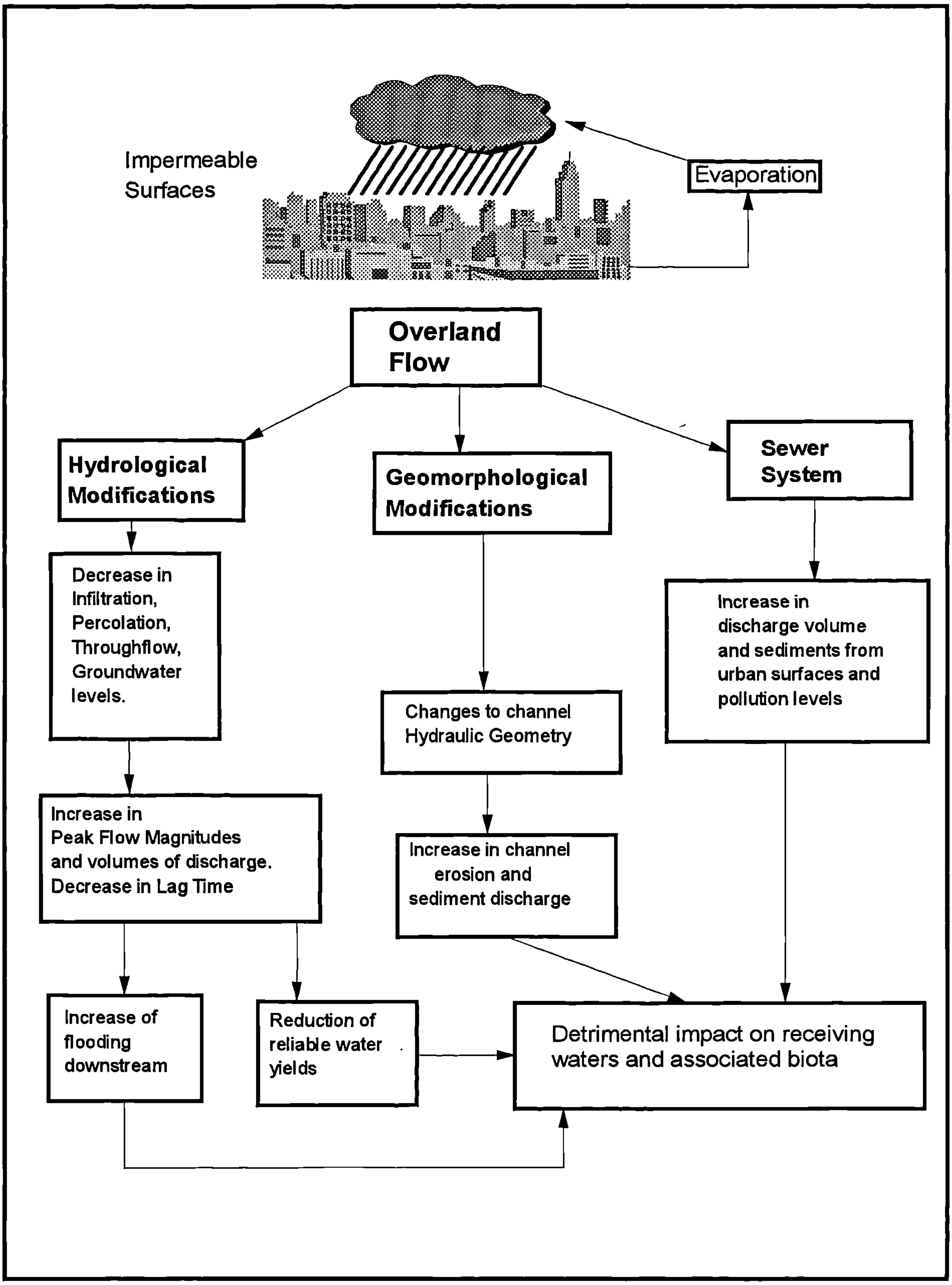


Figure 2.1 **The problems associated with an increase in impermeable surfaces in the urban environment.**

Modifications to the hydrological cycle in the urban environment include:

1) a decrease in infiltration and percolation;

2) a decrease in throughflow and water reaching the aeration zone;

3) a decrease in base-flow in streams;

4) a decrease in the level of groundwater; and

5) an increase of water conveyed via sewer systems.

(Field *et al.*, 1982)

The first two modifications inevitably influence, or cause, the third and fourth changes. A decrease in the volume of water contributing to base flow, suggests that groundwater levels will also have decreased (Schumm, 1977). A continuous decrease in groundwater levels may eventually result in the cessation of groundwater abstraction if an aquifer is used to supply water.

This disruption to the water balance can have long-term implications for groundwater availability and base-flow contributing to the river system. In the National Rivers Authority (NRA) Water Resources Strategy (NRA, 1992), it was stated that abstraction of ground and surface waters have reduced river flows to unacceptable levels. Over forty such rivers in the UK have experienced unacceptable periods of low flows. If authorised licensed abstractions were revoked, 2% (on average) of the reliable yield of water for consumption in England and Wales would be lost. It would be preferable to maintain or revert to pre-development hydrological conditions and promote recharge of groundwater than have to deal with the problems associated with a decrease in the reliable yield.

The water that is prevented from infiltrating into the ground produces overland flow and the increase in overland flow must be accommodated within the drainage system if flooding is to be avoided in the urban environment (Walling, 1981). Increasing runoff volumes in sewer systems is also problematic (Lindbeck, 1984). Within the UK, the sewer systems in many areas were designed during the nineteenth century. The volume of sewage to be removed was less during that time, with the population being smaller and the sewer connections fewer (Shaw, 1994). There have been a number of reports of sewer pipes collapsing under the more recent increased flows (Crabtree, 1988;Shaw, 1994).

One attempt to reduce hydraulic overloading considers attempts to reduce the flows entering the drainage system. Colyer (1983) discusses this approach when he summarises the Hydraulics Research Station report (Hydraulics Research, 1982) which studied flow reduction in drainage systems. Two suggested methods of reduction were preventative entry and attenuation of peak flows. The most effective methods proposed were:

1. restriction of flow from pitched roofs by passing more runoff to permeable areas;
2. similar controls of the runoff from other paved surfaces;
3. the use of attenuation storage tanks;
4. the use of semi-permeable road pavements providing temporary storage of rainfall and other benefits, such as reduced splash and spray.

The disruption to the water balance caused by a reduction of infiltration and natural recharge is clearly a cause of concern for the NRA. Their water resources strategy (NRA, 1992) identified that the demand for water resources in different regions is increasing. It was also shown that only 10% of effective rainfall was needed to meet abstraction requirements.

Unfortunately, the supply of rainfall is temporally variable and it's distribution is influenced by west to east contrasts in rainfall amounts in the UK (Rodda et al., 1976; Shaw, 1994), which results in the east of England receiving less rainfall, a part of the country where demand is high. For example, the NRA calculate that the East Anglian region has a demand for potable water of 1820 Mld (see glossary list) (NRA, 1992): this demand has been projected to increase by the year 2021 by 42%. Anglian region already finds difficulties in supplying the demand required at present. The NRA is considering a number of projects to alleviate the encroaching supply/demand problem (NRA, 1992) and at present transfers water from the River Ouse to supplement a number of Essex rivers.

Perhaps one simple precaution might be to ensure that all future developments in the urban environment attempt to maintain the existing infiltration rates, thus at least maintaining groundwater and river yields at the present level.

2.1.2 Geomorphological Modifications.

The various impacts on fluvial geomorphology by urbanisation have been well documented (Wolman, 1967; Hammer, 1972; Gregory and Park, 1976; Park, 1977; Riordan *et al.*, 1978; Knight, 1979; Petts, 1979; Walling, 1979; Whipple, 1981). The most important impact is associated with the increased flow volumes within the urbanised drainage basin which alters channel flow regime.

The increase in overland flow and storm flow volumes may cause changes to the hydraulic geometry of receiving channels (see glossary Appendix B) by modifying the width, depth, slope or velocity in the channel (Leopold and Maddock, 1953). This may in turn cause an increase in the shear stress acting on the channel boundaries (Bagnold, 1977) which may in turn increase the potential for sediment entrainment (Ferguson, 1987) and enlargement of the channel (Hammer, 1972).

It has also been frequently argued that the fluvial environment will adjust to the dominant discharge (which is the most effective at controlling the channel regime), which are the flows associated with a 1.5 - 2 year recurrence interval storm event (Leopold and Maddock, 1953). If flow volumes increase due to urbanisation, the discharge volume associated with the 1.5 year recurrence interval would be higher and the channel would adjust in an attempt to accommodate the greater discharges.

An increase in rapid transfer of water in the urban environment caused by overland flow and stormwater discharge (in comparison with the natural transfer of water) will also cause an increase in the peak flow magnitudes and a decrease in the lag time. For example channel erosion, resulting from an increase in the peak flow, has been studied at Catterick, north Yorkshire (Gregory and Park, 1976). When comparing urban and rural sites, the urban sites had a 150% increase in channel capacity.

There are wider implications when considering changes to the hydraulic geometry and channel regime. Increased shear stresses and changes in channel width, depth, or slope may induce sediment entrainment and bed scour. This will re-mobilise sediments which may have been deposited many years earlier (Trimble, 1981; Richards, 1982). Not only will this cause problems downstream by depositing the entrained sediment, or by adjusting the channel further, it will also have an impact on the established ecology (Carling, 1987).

Modifications to the established biota will occur if there is a disturbance to the habitats of organisms (Simmons, 1981; Hellawell, 1986). This occurs through a number of mechanisms which include winnowing of fine silts from the bed, bed mobilisation; bank erosion; or sediment deposition. Changes in the quality of bed sediments may cause damage to trout and salmon spawning habitats and other established ecologies, for example, freshwater invertebrate populations (Luedthe and Brusven, 1976). The re-mobilisation of sediment will have a secondary and a possibly more damaging (long-term) effect on the freshwater ecology.

It has been documented (Thoms,1987; Elliott and Pratt,1989) that the pollutant loadings within river and lake sediments in urban areas can be greatly increased in comparison with rural areas. For example heavy metal concentrations in the sediments in the River Tame, UK, have been found to be 3000 times greater than background concentrations in rural rivers (Thoms, 1987). The re-mobilisation of sediments and their associated pollutants may cause changes to water chemistry and quality (Ongley *et al.*, 1981; Förstner and Wittman, 1983; Morrison *et al.*, 1990).

2.1.3 A suggested solution.

If pre-development hydrological conditions could be maintained in the urban catchment, the impact of urbanisation on the fluvial system would be less dramatic. Realistically, this would be extremely difficult to attain during future development (Jenkins and Maskell, 1990), but attempts could and should be made to reduce overland flow and stormwater drainage, to increase infiltration and to maintain a near-natural water balance.

Source control and infiltration techniques attempt to store precipitation where it falls and, where ground conditions allow, dispose of the water into the ground in the adjacent areas. The use of source control has the advantages of retarding storm flows within the system by on-site storage and, consequently, reducing the discharge volumes which have to be accommodated in downstream sewers and watercourses (Amaki, 1990). This will be an advantage both to the engineer and the environment since the hydraulic load on the sewer system will be reduced and a more "natural" hydrological cycle will be maintained. The increased movement of water through the aeration zone will eventually create better conditions for groundwater recharge provided the pollutant loading can be minimised.

Permeable pavements are specifically designed in an attempt to increase infiltration rates. In addition to their potential for decreasing storm flows and allowing water to be lost by evaporation (Jackson and Ragan,1974; Carleton,1990,a), they may through appropriate design, be used to decrease the pollutant loads of infiltrating waters (Aulenbach,1988; Rajapakse and Ives,1990).

2.1.4 Water Quality.

The urban environment concentrates populations and pollutants associated with anthropogenic activities (especially heavy metals (Nriagu, 1979; Gibson and Farmer, 1984)).

2.1.5 The impact of contaminants.

What is contamination ?.

Contamination occurs when pollutants are introduced into a system. Pollution has been defined by the Royal Commission on Environmental Pollution (1984) as:

the introduction by man into the environment of substances or energy liable to cause hazards to human health, harm to living resources and ecological systems, damage to structures or amenity, or interference with legitimate uses of the environment. (p46)

<u>*Sources of pollutants.*</u>

Within the human-created environment there are many sources of pollutants including: atmospheric fallout; industrial effluent; domestic effluent, which includes incinerator emissions; vehicles; leaching from waste dumps; and urban stormwater runoff. The various sources can generally be divided into two broad categories which are:

a) Point pollution sources;

b) Non-point pollution sources

(Förstner, 1979; Walling, 1981; Förstner and Wittmann, 1983). Point pollution sources occur where the pollutants are emitted into the environment from a single source. These are usually easier to both control and monitor. Non-point pollutant sources are more difficult to monitor, examples being atmospheric fall-out and the application of de-icing salts on roads (Novothny, 1984; Brinkman, 1985).

Rutherford (1988) outlined nine sources of pollutants specifically associated with toxic heavy metals:

a)Animal metabolic processes

b)Sewage, sludge and effluent

c)Domestic waste disposal (point source)

d)Industrial waste disposal (point source)

e)Agricultural plant protection and fertiliser application f)Urban expansion

g)Industrial extraction processes: smelting and mining

h)Precipitation

i)Automobiles.

Six out of the nine listed above are non-point pollution sources, with only domestic waste, sewage and industrial waste being point pollution sources, however, there will be a proportion of these two which will eventually be incorporated into the non-point pollution category. For example, emissions from incinerators burning industrial and domestic waste are often dispersed to urban surfaces (Elliott and Pratt,1989).

With a point pollution source, discharge consents formatted within a legislative framework (for example the Water Resources Act (1991); Surface Waters (Dangerous Substances (Classification) Regulations 1989 (SI 1989 No.2286;HMSO)), can be established in order to regulate the concentration of pollution that is discharged into receiving waters. This will reduce the possibility of accidental acute shocks of pollutants entering the fresh-water system, but it may produce chronic long-term effects (Thoms, 1987; Crabtree and Clifforde, 1989). However, once a discharge consent has been established, it is at least possible to monitor the pollutant discharge and possibly reduce it.

Non-point pollution discharges are more difficult to quantify and it becomes more difficult to establish a budget for emissions within an environmental system (Field and Pitt, 1990). It has been shown, for example by Loehr (1984), that overland flow and streamflow are the main carriers of non-point pollution. This is because there is a higher percentage of runoff which is "overland" and which reaches the drainage system rather than infiltrating into the ground.

Non-point pollutant sources in the urban environment have been associated with industrial developments (Whipple, 1981) and high levels of heavy metals have been linked with road pollution (Hedley and Lockley, 1975; Hamilton-Taylor, 1979; Hamilton *et al.*, 1984; Morrison *et al.*, 1984; Palmgren and Bennerstedt, 1984; Williams, 1987; Warren and Birch, 1987), especially cadmium, which is produced by the attrition of car tyres (Johnston and Harrison, 1984). Road surfaces are not usually permeable and the pollutants rest on the surface where they are entrained during overland flow (Diniz, 1978).

Lindholm and Balmer (1978) observed a correlation between pollutant loadings and the percentage area of impermeable surfaces in the catchment. They also observed that runoff occurs only for 5-10% of the year, with the consequent effect that pollutant loadings are concentrated during this short time. For example, they monitored the runoff from a 15 minute rainfall event and found that the concentration of organic matter from a 10 ha catchment had similar levels to untreated domestic sewage from 160,000 people. Bradford (1977) also showed that the shock load of urban stormwater runoff could be 100 to 1000 times greater than sanitary waste water. This is possibly due to the fact that when urban stormwater runoff occurs it entrains pollutants which have been gathering on urban surfaces over long periods of time and transports them often within a small total volume of water.

In order to reduce these concentrations the percentage area of impermeable surfaces could be decreased, thus encouraging the attenuation of storm flows within the urban environment and increasing the possibility of on-site retention of sediment-associated pollutants.

It has been observed that the degree of sediment-associated pollution in urban areas can be at least four times greater than that found in rural areas (Nriagu, 1979; Ellis and Revitt, 1982; Lord, 1987; Elliott and Pratt, 1989). Figure 2.2 illustrates the pathways of dissolved and sediment-associated pollutants within the urban environment (Förstner, 1979).

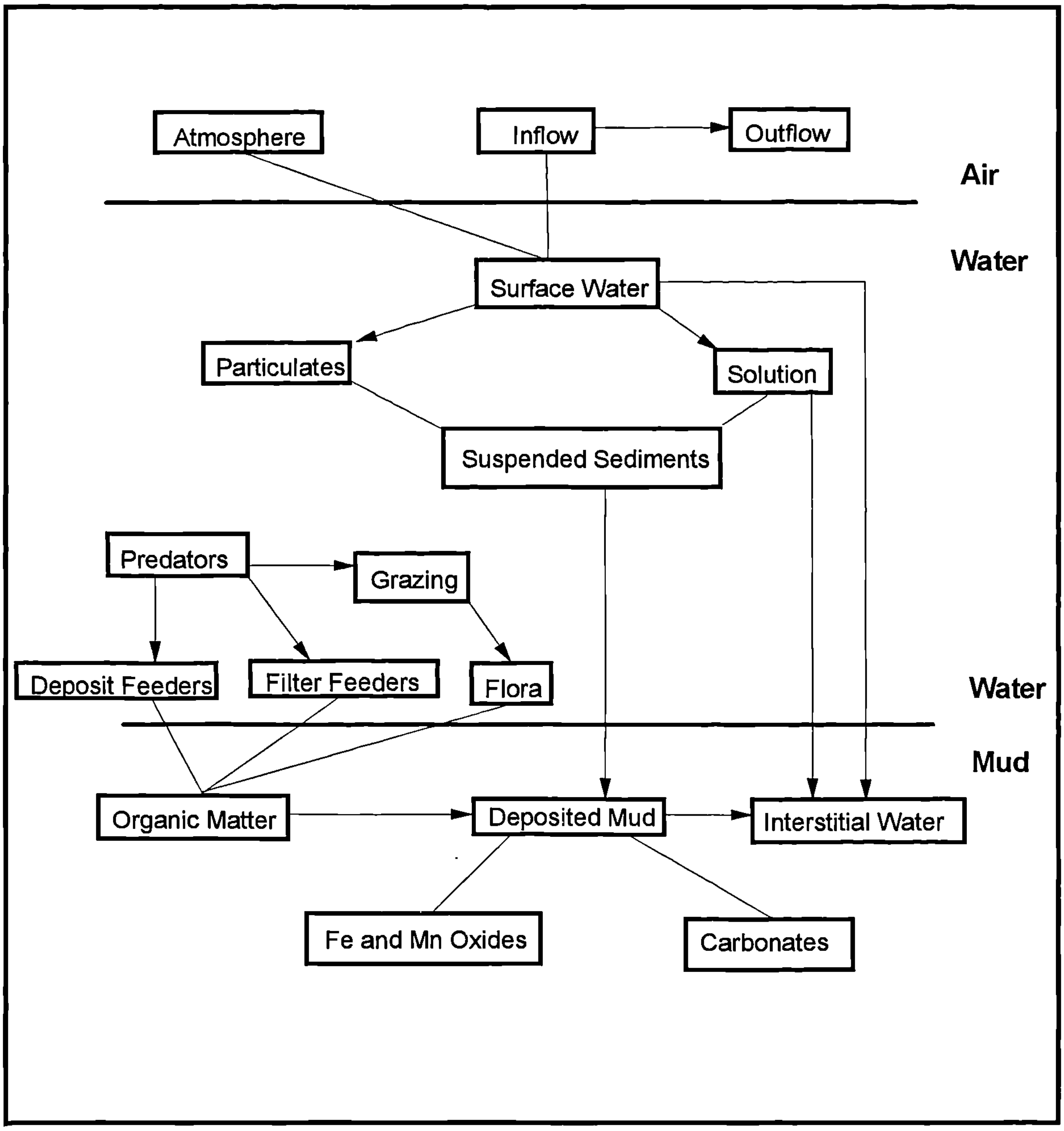


Figure 2.2 **The pathways of pollutants within the urban environment (after Förstner, 1979).**

Concentration of pollutants and the "first flush" phenomenon.

Within the urban environment, pollutants will rest on the impermeable surfaces until they are removed by sweeping and aeolian processes, or are incorporated into urban stormwater runoff which is generated during a precipitation event. The residence time of these pollutants depends on the magnitude and frequency of precipitation events, but residence time is usually not as long as the possible residence time on "natural" surfaces. Once pollutants are entrained within the stormwater runoff, the peak concentrations are usually in advance of the peak water discharge (Förstner and Wittmann, 1983; Knighton,1987). This is often referred to as the first flush phenomenon.

Non-point pollution discharge cannot be regulated; it is influenced by a number of factors; for example pollutant dispersal on roads is influenced by density of traffic, wind speed and direction (Jones and Tinker, 1984), intensity and duration of rainfall events. However, removal of particulate-associated pollutants during the early rising stages of the hydrograph inevitably means a short, but concentrated, shock of pollutants to the stormwater runoff and receiving watercourses (Lindholm and Balmer, 1978). It is not the pollutant loading over the year that is important, it is the concentration at a certain time and the dilution of these concentrations, which govern the survival of freshwater biota.

The first flush of pollutant loads in runoff can be controlled by the use of combined sewer systems (Cherrered and Chocat, 1990), which allow the most polluted water during the initial stages of the hydrograph to be directed to treatment plants. The less polluted water can then be re-directed, if necessary, into fresh-water systems. Whipple,(1981) illustrated the benefits of using detention basins to allow particulates and their associated pollutants to settle from the stormwater runoff, showing that 14-34% of total sediments were removed during peak flows and 83-90% of annual suspended sediment load was removed, if detention storage was released over a 30-40 hour period. Mesuere and Fish (1989) also discovered that small-scale detention ponds are a useful management practice for controlling runoff and the associated pollutants from parking areas. These practices were seen to reduce the pollutant concentrations reaching receiving waters.

Research has also shown that polluted stormwaters are placing stress on receiving water systems (Ellis, 1989). The provision of roads for the increasing traffic flows exacerbates metallic and organic pollutant loadings (Johnston and Harrison, 1984; Lygren *et al.*, 1984; Mikalsen, 1984; Lord, 1987). Yousef and Wanielista (1986) discussed the stormwater runoff from highway bridges over lakes where they found that the heavy metals in dissolved form settle out at the point of release into the lakes and become immobilised on sediments. The sediment on the bottom of the receiving waters holds the heavy metals and the benthic organisms accumulate high concentrations of heavy metals. They suggested that stormwater percolation in adjacent land should be encouraged with the removal of heavy metals before the runoff reaches the receiving waters. Research suggests that detention devices of some kind would be of benefit in order to reduce the impact on receiving systems.

Numerous research projects have shown that heavy metal concentrations are associated with the sediments on which they adsorb (Hamilton-Taylor, 1979; Förstner and Wittmann, 1983; Mesuere and Fish, 1989; Ellis, 1990), with cation exchange capacity generally increasing with a decrease in grain size (Kennedy, 1965). Heavy metals in the urban environment have significant health impacts on the population; for example, Gibson and Farmer (1984), studied the lead ingestion by young children in Glasgow and found that on average they ingest 100 mg of dust per day which has a daily mass of lead of 26 micrograms.

Cline and Upchurch (1973) found that heavy metal concentrations are correlated with organic carbon concentrations and that in soils the upper 5-10 cm are where concentrations are greatest, although this was dependent on bacterial absorption mechanisms. Ellis (1990), also found that the presence of organic material was important for pollutant removal. He suggested that the removal of solids in stormwater runoff through sedimentation and filtration can effectively reduce the pollutant load.

Measurements of heavy metal concentrations near roads have shown a dramatic decrease in concentration with an increase in the distance from the road surface (Johnston and Harrison, 1984; Lygren *et al.*, 1984; Jones and Tinker, 1984; Warren and Birch, 1987; Deronne-Bauvin *et al.*, 1987; Williams, 1987; Tam *et al.*, 1987). If sediments contained in stormwater runoff can be retained on-site, either by filtration or sedimentation within the road surface, the pollution associated with the sediments can be retained, thereby reducing the pollutant concentration in stormwater runoff which reaches the watercourses.

A gravel matrix can effectively filter turbid water; for example stormwater runoff with a sediment load (Rajapakse and Ives, 1990). Sand column infiltration experiments have also shown that heavy metals can be removed by simply directing sediment-loaded waters over sand (Aulenbach and Chan, 1988). Since most stormwater runoff contains sediment particles (Ellis et al., 1982), especially clays and silts, a simple gravel matrix (for example below a car park surface) could be used to act as a primary screening site for sediments in stormwater runoff.

2.1.6 Conclusion.

There seem to be two main problems to approach when attempting to alleviate the detrimental environmental impacts of urbanisation; firstly, the return to, or maintenance of, quasi-natural runoff conditions and, secondly, the reduction and control of sediment-associated pollutants as they move through the urban drainage system. The logical direction of research would be to analyze the possibilities for retaining any excess runoff and pollutant loadings at source, with the intention of producing on-site reductions. With respect to the hydrological problems outlined above, this avenue of reasoning would allow precipitation to be directed into the ground. If a more natural hydrological response could be created, then the pollutants might be held on-site and filtered within suitable structures, causing the source area to be a managed sink for pollutants. This would decrease the sediment-associated pollutant loadings and concentrations in stormwater discharges within the storm sewers and also in those reaching the receiving surface water and groundwater systems.

Results concerning the use of stormwater infiltration systems indicate that stormwater discharges within urban areas can be physically reduced by on-site storage (Raimbault,1990). This has been shown to reduce stormwater volumes reaching the sewers by 30% (Field et al., 1982), which helps to alleviate the overloading of stormwater sewers, producing a slower rate of water movement within the urban system. Research on these techniques has shown an attenuation in the storm hydrograph (Raimbault,1990) but, in comparison, there has been little analysis focusing on the sediment/pollutant retention possibilities of such systems. It is imperative that more intensive research should be directed to study both the rainfall and pollutant retention mechanisms within stormwater infiltration systems. The next section reviews the historical approach of engineers and hydrologists to the control of stormwater runoff since the 1960s.

2.2 Changes in philosophy in the control of urban runoff

2.2.1 Philosophical changes, 1960s-1970s.

The traditional approach to the control of increased stormwater runoff in urban areas has been an "end of pipe" solution (Newson, 1992). Such a solution evacuates the runoff quickly from problem areas via man-made conduits to areas, usually on the outskirts of the urban environment, where it can be dealt with. This approach is the antithesis of integrated catchment planning, whereby smaller scale controls are exercised throughout the whole catchment in an attempt to control the increase in stormwater discharges (Gardiner, 1991). A change in the philosophy to urban stormwater control by the engineer can be seen from the 1960s onwards (Mc Pherson, 1977).

The problems associated with increases in stormwater discharges were well documented (Leopold, 1968), as was the need to alleviate the detrimental impacts downstream. By the early 1970s, data from a number of research projects (eg; McPherson, 1977; Aitken, 1977) had been collated and preliminary suggestions for the alleviation of urban stormwater problems were proposed. Papers presented at a number of symposia and meetings (e.g McPherson, 1977) illustrated that there was a need to model the effect that urbanisation was having on the hydrological cycle. The research undertaken involved comparative studies; for example studies on paved and unpaved areas and on pre/post-development impacts on basin hydrology (McPherson,1977). This research led to a better understanding of the impact which humanity was having on the hydrological regime in the environment and the benefits of using new "state-of-the-art" techniques to minimise the impacts downstream.

Following these developments, a number of models were developed which examined the effects that varying rainfall intensities and durations would produce on the drainage system. These included the development of planning models, design/analysis models and operational models (Mc Pherson, 1977).

By the mid 1970s a secondary anthropogenic impact was beginning to be appreciated i.e. the poor quality of urban stormwater runoff. It was obvious at the time that many countries had not considered this problem (Ramashars and Sarma, 1977; Marsalek, 1977). However, a number of Scandinavian countries, as well as America, Australia and Germany, had started to study the quality of stormwaters (Aitken, 1977; Lindh, 1977; Lindholm and Balmer, 1978) in addition to changes in hydrological response.

2.2.2 Philosophical changes, 1980s onwards.

By the 1980s emphasis in the engineering hydrological literature was being placed on methods of detaining stormwaters. Australian interest in urban hydrology had expanded (since Aitken, 1976) and research was promoted into the study of detention systems, especially on-site retention storage (Carleton, 1990). Modelling of rainfall/runoff relationships had begun and the awareness of the impacts of stormwater quality was growing rapidly (Carleton, 1990). A similar situation existed in Canada where research concentrated on urban runoff data and on the impacts that the stormwater quality had on receiving waters (Marsalek, 1977). Storage ponds and inlet controls for "dual" drainage or combined systems were researched.

Developments in the U.K. included the completion and release of the Wallingford Procedure (Lowing, 1977); urban catchment research (including pollution analysis) and a number of specialist studies, which monitored pollution runoff from urban areas (Fletcher et al, 1978; Pratt and Adams, 1984). Flow reduction in the drainage system was also studied, with research suggesting a number of ways in which peak flows could be attenuated. This included designs to pass more roof runoff to permeable areas; using attenuating storage tanks to control runoff from paved areas; and the use of semi-permeable roads or pavements (Colyer, 1977).

In Sweden, studies illustrated the importance of using both separate and combined stormwater sewers appropriately (Lindh, 1977). The Netherlands were more experienced in the use of combined systems after investing a great deal of capital in urban stormwater control (Lindh, 1977). Infiltration research was well established, as was the monitoring of stormwater quality (Zuidema, 1977). Finland also had developed research into stormwater infiltration primarily using retention basins, but it was apparent that the effect of fine material on infiltration, which caused clogging, needed to be researched further (Zuidema, 1977).

In France, the main approach to reducing peak flows was to use retention basins and porous roadways (Desbordes and Normand, 1983; Balades and Chantre, 1990). This research was one of the more progressive in Europe, which had already seen significant advances in the modelling of urban runoff by the 1970s. During the 1980s urban runoff pollution levels were identified as being a cause for concern (Raimbault *et al.*, 1982). One approach to solve this problem was to reduce the quantity and increase the quality by:

a)retarding the flow in the drainage system;

b)reducing the flows entering the sewer system and;

c)reducing the contact time of stormwaters with the pollutants.

Desbordes and Hémain (1990) also discussed further research needs concerning the impact assessment of urban stormwater pollution. Stormwater infiltration systems were beginning to be developed and the phrase "source control" was being widely used (Desbordes and Normand, 1983; Balades and Chantre, 1990; Raimbault, 1990: Pratt, 1995).

In general, the approach to the control of urban stormwater had moved, at least internationally if not in the UK, from the use of traditional "end of pipe" solutions (using detention structures and other financially and land-intensive strategies) to a catchment management strategy (using local small-scale, on-site control methods). The following section describes some of the techniques and devices used.

2.3 Approaches used to control urban runoff

The control of urban runoff has been approached from numerous directions which can be summarised into four main categories:

i) an increase in the capacity of the drainage system;

ii) control of the flows entering the sewer system and watercourses;

iii) attenuation of flows within the drainage system;

iv) reduction of flows entering the drainage system.

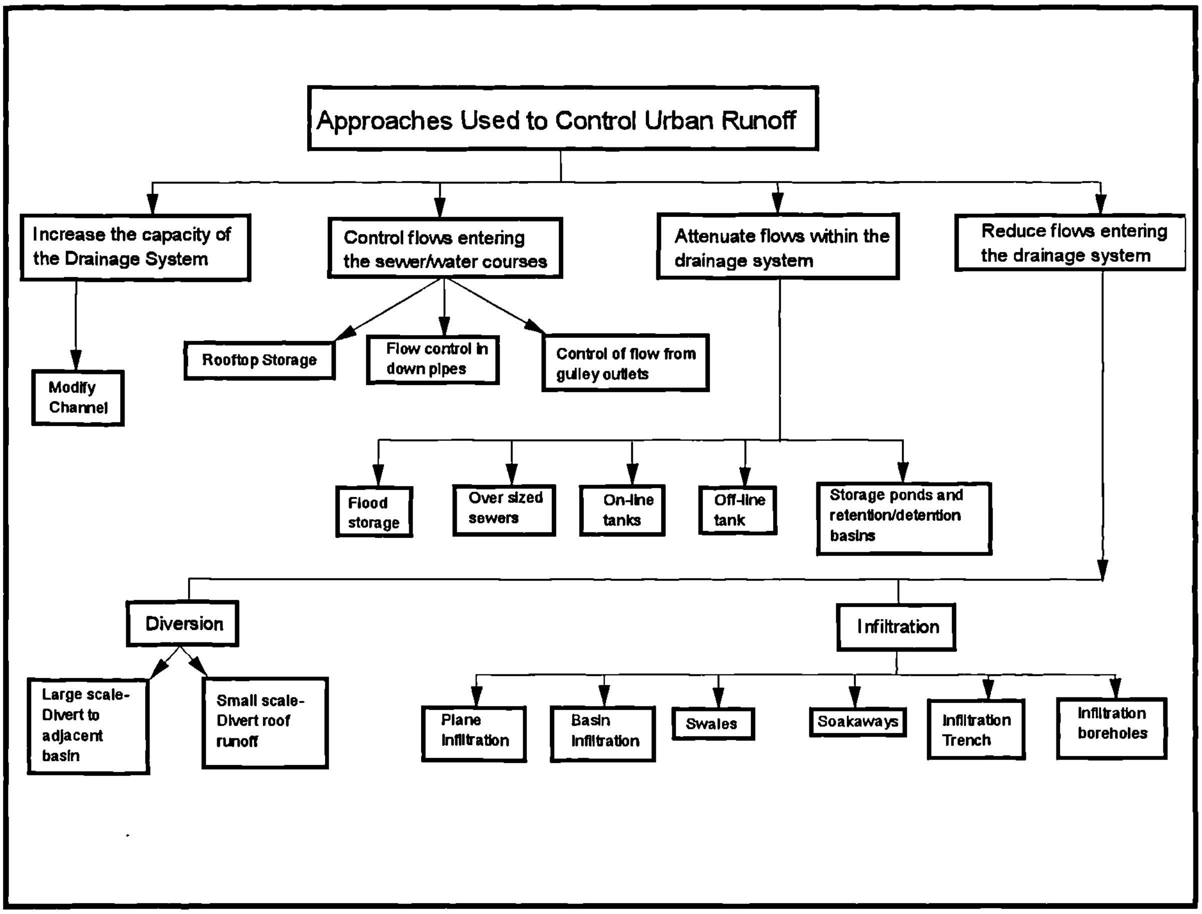


Figure 2.3. The traditional and modern approaches used to control urban stormwater runoff.

These approaches are summarised in Figure 2.3.

2.3.1 Increasing the capacity of the drainage system

Within the natural drainage system this method involves channel enlargement works by deepening the channel (by dredging); raising the river banks; or widening the channel in an attempt to increase the capacity of the drainage system, thus confining waters that may derive from flooding upstream (Keller, 1976; Gardiner, 1991). The urban drainage system can be enlarged by the installation of large sewer networks with oversized pipes; but the disadvantages include economic factors and the disruption of the urban environment and the drainage system downstream. However, if no alternatives are available, it is generally considered favourable to convey the runoff downstream as efficiently and quickly as possible (Gardiner, 1991).

This strategy echoes the traditional "end of pipe" solution to urban runoff problems. With the growth of integrated catchment planning and sustainable management, this approach of transferring the problem downstream is unlikely to be tolerated by the regulating authorities.

2.3.2 Controlling the flows entering the sewer or water-courses

This approach aims to divert, or attenuate, the flows before they reach the main drainage system. Techniques include:

a) *roof top storage*, which has the advantage of maximising the attenuation of the storm hydrograph and the reduction of peak flows in the sewers (Balmforth, 1990), but has the disadvantage of high installation costs and stress to the building. About 60% of stormwater is derived from roof surfaces and the reduction of roof water discharges by on-site storage has a more significant impact on downstream flows than corresponding interception of runoff from paved surfaces during the same storm event (Pratt and Harrison, 1982).

b)*Flow control in downpipes*, directs the flow from roof surfaces into storage tanks or underground chambers instead of into the drainage system. The disadvantages of these systems include difficulty in outflow control; device maintenance; and the regulatory authorities lack of interest in adopting such systems due to their non-permanent nature (Beale, 1992).

c)*Control of flow from gulley outlets,* which restrict or reduce the capacity of the outlet pipe consequently allowing, under extreme conditions, surface flooding in non-critical areas, such as car parks (Zeno and Palmer, 1986).

2.3.3 Attenuation of flows.

Attenuation is, in general, the reduction of peaks in the storm hydrographs through the extension of the period of discharge, thus avoiding periodic overloading of the drainage system (Whittow, 1984). By reducing these peaks in discharge, the system has more chance of coping with the total flow volume without surface flooding. Various strategies include:

a)*Flood storage.* This strategy re-directs excess flows to areas where surface detention or retention is tolerated, providing a localised cost-effective method of dealing with excessive discharges. Partial retention systems have been beneficial in Orlando (USA), allowing for the attenuation of the hydrograph and a reduction in the pollutant load entering surface waters (Zeno and Palmer, 1986). By on-site retention of the first 12.5 mm of rainfall, some 80-85% of pollutant loads were controlled and prevented from entering the receiving waters (Zeno and Palmer, 1986). The water retained can then infiltrate or evaporate, but the water retained must be disposed of within 72 hours to provide for storage volume for subsequent events.

b)*Oversize sewers.* This strategy allows flood discharge to be stored subterraneously, where surface flooding is not possible. However, sewer dimensions must ensure that the pipe design has a channel which will reduce the possibility of sediment deposition (Beale, 1992).

c)*On-line tanks.* This strategy incorporates storage tanks along the length of the sewer system. The outlet structure to a tank controls the release from storage. Outlet control can be an orifice; a throttle pipe; a flume or weir; or a vortex control, such as a hydrobrake. The precision of control of these systems will depend on requirements and costs may be high (Novotny, 1984: Novotny, 1994).

d)*Off-line tanks.* This strategy diverts flow to storage tanks that are separate from the drainage system. Return into the sewer system can be by gravity or by pump (Beale, 1992).

e)*Storage ponds and retention/detention basins.*
This strategy allows for storm sewer flows to be stored on the surface or below ground. These systems can be on-line or off-line and often have a secondary advantage of pollution control (Whipple, 1981; Yousef and Wanielista, 1986; Livingston, 1986). These basins are usually man-made and differ from (a), since their primary function is storage over an extended period of time. Jacobsen (1993) suggested that the infiltration of stormwater, instead of just detaining it, would have a positive effect by reducing the loadings which reach treatment facilities.

2.3.4 Reduce flows entering the drainage system

This approach has two main strategies, namely diversion and infiltration.
a)*Diversion.* On a macro-scale this strategy incorporates the diversion of flows into adjacent catchments, but the applicability is limited due to cost and to the feasibility of adjacent catchments being able to cope with the increase in discharge volumes (Beale, 1992). On a micro-scale diversion can be achieved by diverting roof runoff onto grassy areas or surfaces

which allow for direct infiltration. The percentage area of roof surface in an urban area is relatively high; approximately half of the sealed surface in urban areas in central Europe (Förster, 1992). This method could be an effective way of reducing flows entering the drainage system (Hydraulics Research, 1982).

b)*Infiltration.* Infiltration and source control techniques are receiving more interest internationally as regulating bodies adopt them (CIRIA, 1992). In the UK, this technique has been used for decades, even centuries (CIRIA, 1992) but lack of long-term performance details has meant that their formal adoption has been slow. The method removes surface runoff from the drainage system by allowing it to infiltrate into the soil, increasing the possibility of recharge to groundwater and also increasing the opportunity of water loss by evaporation. This method attempts to maintain pre-development runoff levels by encouraging infiltration, thus reducing runoff volume and velocities, and also attenuating the storm hydrograph. There are a number of strategies adopted namely:

i)*Plane infiltration.* This strategy uses flat, grassed or paved areas as a surface through which the runoff can infiltrate (Stahre, 1992). If the sub-soil is impermeable, drains may be installed and the throughflow can be dispersed into a drainage system or, alternatively, into a grey water system for re-use (Pratt, 1993). If the latter procedure is implemented, the system becomes more of an attenuation device.

ii)*Basin infiltration.* This method conveys runoff from other areas to a basin where infiltration can occur at ground surface level in the retention area. This strategy can enhance the aesthetic qualities of the urban area (Amaki, 1990), with the design of the system being dependent on the location and the possible dual use of the surface, i.e., for car parks or landscaping. Maintenance of these systems is relatively simple, but the responsibility for the maintenance will depend on the location of the device (CIRIA, Vol.2, 1992).

iii)*Swales*. This method allows for the storage and infiltration of runoff in shallow-sloped, grassed ditches (side slopes typically of 1:4 or less to allow easy maintenance). They are common in North America (Scholl, 1987) and have the advantage of adding to the aesthetic quality of urban developments. These systems can also be used to convey runoff to a more central infiltration device.

iv)*Soakaways*. This method of infiltration is common in the UK, previously being used in areas remote from a sewer or watercourse. More recently, these systems have been used in urban areas to reduce the runoff volumes. The BRE Digest 151 (1973) design approach stated that assuming that the soakaway is cylindrical in shape, with a diameter equal to the effective depth, the soakaway is sized such that the rate of exfiltration from the soakaway into the surrounding soil equals the design rainfall rate, which has been taken as 15 mm h^{-1}, being equivalent, on average, to that occurring in a 2 hour storm once in 10 years.

The design of soakaways has been updated recently (BRE, 1991) allowing the size to be determined from specified shape and soil infiltration characteristics. Construction of these devices may take many forms, being singular or linked, and may use a range of materials, depending on requirements. Hydraulics Research Ltd have recently completed a project examining the design and the performance of these systems (Watkins, 1992).

v) *Infiltration trench.* These systems are stone-filled trenches which can receive runoff directly from the surface or through perforated or porous pipes. They are more effective than circular or square soakaways since they have a greater surface area for exfiltration relative to the volume of storage. They are a popular method used in Sweden mainly for the infiltration of roof runoff (Holmstrand, 1984; Jonasson, 1984). Japan has used this technique in its experimental sewerage system in the northwest area of Tokyo (Fujita, 1993). Peak flow reduction has been shown to reach 60% and both the cost of construction and the reduction in the acquisition of land makes the use of these systems very favourable.

vi)*Infiltration boreholes.* This method is not used to a great extent in the UK, often being restricted to the infiltration of less polluted runoff, such as that coming from roof surfaces (Beale, 1992).

Infiltration techniques are, in general, small scale and are usually used as an on-site strategy to reduce the volume of stormwater entering the sewer system. By controlling the discharges on-site, in an attempt to maintain pre-development discharge rates, the problems associated with larger detention devices (i.e. land acquisition, cost and maintenance) are reduced (Amaki, 1990). The main problem to overcome with the use of these infiltration techniques is that their maintenance requirements are still relatively unknown in the UK and a lack of performance knowledge hinders their adoption by water companies and regulating authorities.

2.4 Specific research on permeable/porous pavements.

There are many strategies employed to counteract the detrimental impacts of urban runoff. The research aims of this project were to examine the hydrological behaviour of one of these structures, a type of plane infiltration system known as porous/permeable pavements. Previous research illustrating the advantages and disadvantages of using this technique of stormwater control will be examined in the subsequent discussion.

There are two main types of engineered permeable pavement: the first being composed of a porous Macadam surface and the second being formed from concrete blocks or lattice paving. The first option has a greater structural strength and, therefore, has a wider applicability to the urban road system.

Different countries have differing approaches and designs and examples from a number of countries will be examined independently.

2.4.1 Permeable pavement research in America.

There are various types of porous/permeable pavement ranging from permeable Macadam to concrete porous pavements, such as grasstone and grasscrete. Their uses are limited usually to parking areas and roads carrying light loads. Field *et al.* (1982) gave an overview of porous pavement research in America. The paper discussed how the approach to stormwater management had moved from quick elimination of the runoff to the adoption of techniques that attempted to maintain the natural or pre-development runoff levels through on-site controls. Design philosophy was discussed, as were a number of projects, for example EPA research projects, at Rochester,(Murphy *et al.*, 1981). The research in Rochester on two parking sites illustrated a number of positive benefits of using these surfaces, especially the fact that the peak runoff was reduced by as much as 83% and that the structural integrity of the surface, even after 100 freeze-thaw cycles, was maintained.

Another advantage of using permeable Macadam is that the drainage capacity of the surface allows surface water to be removed effectively, thus eliminating vehicle hydroplaning, because the coefficient of friction between the vehicle tyre and the surface (highway or runway) is similar to that of dry conditions (Jones, 1973; Field *et al.*, 1982).

The Maryland Department of Natural Resources published a Standards and Specifications for Infiltration Practices (Anon, 1984), which included a section on the design of porous macadam pavements. The discussion included feasibility testing methods, design methods and design procurement. In general the design method was based on controlling the runoff resulting from a specific frequency of storm event. The required design volume of the sub-base stone was calculated from equation 2.4.1.

$$V_w = Q_c A_c + PA_p - FTA_p \qquad \textbf{Equation 2.4.1}$$

V_w=Volume of water that must be stored

$Q_c A_c$=runoff volume from the adjacent contributing area

PA_p=Rainfall volume falling on the porous macadam pavement

FTA_p=exfiltration volume into the underlying soil.

The design method dimensioned the structure by minimum depth and minimum area.

Jackson and Ragan (1974) provided a more theoretical approach to the examination of the hydrology of porous pavements, using the Boussinesq equation in order to produce design equations and graphical aids for the engineer. The equations were based on assumptions made by the Franklin Institute Research Laboratories (1972) on the performance of porous pavements. The numerical models gave an insight into the hydrological modifications, if a complete drainage system was constructed using porous pavements. The approach was entirely theoretical and did not consider practical problems, such as surface clogging.

Research on the economics of installing these systems, undertaken by the Franklin Institute (Thelen *et al.*,1972) found that the installation of a conventional pavement with any downstream sewer works due to increased flows was of higher cost than a similar area installed with a porous Macadam pavement which would not cause any downstream sewer works. However, the cost of these systems were very site specific, as was their adoption.

Scholl (1987) illustrated this point in a short paper examining the various techniques considered when a parking lot was designed at the University of Florida. The costs are given in Table 2.4.1.

The porous pavements were not adopted due to the higher construction costs, in particular the transport costs for the import of the stone sub-base material, and due to the limited experience of these systems. Grasscrete structures have also been researched in America. Day *et al.* (1981) illustrated the significance of these structures for decreasing overland discharge and reducing pollution. However, the lattice structures have the disadvantage of low structural strength and decreasing permeability due to compaction of the soil-filled inlets over time.

Table 2.4.1. Costs of surface construction. (After Scholl, 1987).

Porous Pavement	$630,000
Conventional Facilities	$535,000
Difference	$95,000

2.4.2 Permeable pavement research in Sweden.

In Sweden, a permeable/porous pavement, called a "unit superstructure", has been intensively studied since 1981 (Hogland *et al.*, 1987). The first surface was built at Nodinge in 1981. The construction consisted of

a) permeable Macadam, 40 mm thick called Drainor (trade name),with a surface void volume of 15-25% of total volume,

b) an adjustment layer consisting of an aggregate bed (size fraction 8-80 mm some 60-200 mm thick and a sub-base 300-700 mm thick depending on the required storage capacity,

c) a drainage pipe 100 mm diameter installed with sub-base to convey waters out of the construction to a nearby watercourse or sewer (the sites were all on impermeable soils, hence infiltration to groundwater was impossible)

d) a layer of geotextile, which reduced particulate penetration to the sub-grade.

The surface measured 950 m^2. Infiltration tests were carried out 4½ years after the construction of the surface. The results showed an average infiltration rate of 64.8 mm h^{-1} with a maximum of 199.8 mm h^{-1}, which was still 60 times higher than the infiltration capacity of an ordinary old lawn (Hogland *et al.*, 1987).

In Lund, the test areas, built in 1984, comprised two parking areas measuring 470 m^2. A number of other test surfaces were built in Sundsvall. The infiltration capacity of new surfaces ranged from 498-702 mm h^{-1} (Hogland, 1990). The disadvantage of these structures was that they became clogged during the construction phase of the development, mainly because the site workers were untrained to work with this new type of surface. This was also noted in Lund, where the infiltration capacity was dramatically reduced. The surface clogging could only be removed efficiently if brushing and vacuum suction was used in combination with a high pressure spray.

The test sites in Sundsvall were chosen because of the cold climatic conditions in that region. The research identified that the 'unit superstructure' showed the same, or less, sensitivity to frost damage (possibly due to the higher void ratios).

Other research (Niemczynowicz, 1990) reported an 80% decrease in peak flows from the sub-base drains as compared with drain flows from traditional impermeable surfaces, which was significant since these surfaces covered a total of 7,000 km^2 in 1990. However, the volume of runoff will remain the same if the throughflow is evacuated to the sewer system. Overall the cost of construction was estimated to be 25% cheaper than for traditional pavements, because construction was simple and quicker and local stone costs were low.

Pollution studies on these structures have been carried out by Hogland (Hogland, 1990; Hogland *et al.*, 1990). Within the structure (comprising of Macadam, adjustment layer, aggregate bed, drainage pipe in coarse aggregate, a pervious geotextile and the soil), the highest levels of trapped pollutants were detected in the geotextile, which prevented clay particles from penetrating into the soil below the lowest part of the structure. The accumulation of pollutants was suggested to increase with time, which might affect the maintenance requirements. Overall, the pollutant concentrations in all layers were low, but this was partly explained by the age of the structure (being only one-year old), however, there was no significant build up of pollutants in the underlying soil. This was also found to be the case in the laboratory studies which simulated a thirty-year use of the structure (Hogland, 1990).

2.4.3 Permeable pavement research in Japan.

In Japan infiltration devices are used to reduce the flooding by stormwater caused by increased runoff due to urbanisation. Land is limited, so alternative methods for detaining stormwater had to be found which did not demand large land areas for storage (Fujita and Koyama, 1990). Examples included permeable Macadam, which could be used in certain areas (Tsuchiya, 1978). Ichikawa *et al.* (1984), described the use of a pervious pavement at a baseball pitch at the University of Tokyo. The structure included: a) two layers of 50 mm thick pavement, b) 100 mm to 300 mm crushed gravel, c) 50-100 mm sand. The hydrological performance was monitored and it was noted that only 5.9% of the rainfall was discharged. However, the rainfall during the research period was lower than normal.

Fujita (1984) described the experimental sewer system in Tokyo (called the E.S.S.) which had been installed in about 249 ha of urbanised area since 1980, in order to reduce runoff which might cause downstream flooding due to over-bank flows from the Shakujii and Shiako rivers. Flood problems were exacerbated by the fact that the widening of these rivers was restricted by buildings on both banks. Infiltration techniques included permeable pavements, which were laid as footpaths, narrow roads and parking areas. Heavy traffic had caused problems by clogging the structures. Their application has, therefore, been limited to low traffic density areas. Fujita (1993) described the development of the E.S.S. with regards to the use of permeable pavements. In Setagaya, Tokyo, the total road area was 7,600 km^2, of which 354 km^2 or 4.7% being covered with permeable pavements. For the total road area of Tokyo

(149.68 km^2), the estimated area covered by permeable pavements was 3.74 km^2 or 2.5%. Both porous concrete blocks and Macadam were used.

2.4.4 Permeable pavement research in France.

Balades *et al.* (1990), discussed the experiments made by the Bordeaux Municipal Council in the drainage system in order to reduce stormwaters. Large constructions, such as storage reservoirs (eg, beneath football pitches) and other capital intensive projects, have not been adequate to cope with the increasing runoff produced by urbanisation (the surface area which has a risk of flooding was 135 km^2 out of 640 km^2 (Balades *et al.*, 1992)). The council had found it financially difficult to maintain these types of projects and gave itself statutory powers to use "compensating techniques" (infiltration techniques) in an attempt to alleviate these problems. Financially, these techniques were favourable because they reduced costs (those involved with the laying of pipes) by 20-30%. They also had the added advantage of being easy to integrate into the urban environment; and they promoted the maintenance of a quasi-natural hydrological budget.

Permeable pavements (carriageway reservoirs) were used as an integral part of the roads, providing sub-surface reservoirs for rainfall which could be temporarily stored before release into the drainage network. Surface coverings included porous Macadam; foam mortar cement concrete; honeycombed concrete flagstones; ungraded, run-of-pit coarse gravel; and foam mortar paving stones. The choice of surface depended on the site's specific structural requirements. Table 2.4.2 illustrates the storage space available for water in some examples of the sub-structures, which also exhibited adequate mechanical properties.

The clogging of these devices has been reduced by regular maintenance in the form of suction sweeping. Raimbault (1990) discussed aspects of the carriageway structures (porous pavements) including their importance as reservoir structures. He examined the performance of these structures by injecting water into the sub-base areas. Initial results showed that, even though clogging of the surface occurred, it was limited to the top 10 mm, implying that the storage capacity was unaffected. Raimbault discussed a number of projects and illustrated the utilisation of porous pavements (Raimbault *et al.*, 1982; Raimbault *et al.*, 1987). Pollution studies on pervious roads were conducted in 1991 by Colandini (1993) in response to a perceived lack of knowledge on the effects that these systems can have on groundwater. The site was a car park structure with a retention zone of 200 m^2 in Begles (Gironde, France). The structure consisted of a) porous Macadam 80 mm thick, b) 170 mm of coarse bitumen-stabilized graded aggregate, c) cobblestones, d) sand layer, e) geotextile, f) Nidaplast, a honeycomb plastic structure which increases the water storage capacity, g) 150 mm sand. The results indicated that the highest pollutant concentrations were found at the surface and close to the drainage pipes. The conclusion was that regular cleaning of the surface would reduce the risk of pollutants being stored in the structure or, worse, being conveyed through the structure into the groundwater.

Table 2.4.2. Storage space available in sub-structures. (After Balades *et al.*, 1990).

	Bituminous draining base course	Coated draining material	Foam mortar	Nidaplast- ductile honeycombed
Total space	20%	20%	15-25%	90%

2.4.5 Permeable pavement research in the United Kingdom.

The use of permeable pavements for the control of stormwater runoff has had a limited application in the UK, with few examples available. The use of grasscrete and similar concrete lattice structures could be said to be more widespread, with a large selection of commercial products. However, these structures have had a limited use, mainly for aesthetic enhancement, or for economic reasons, being rarely used for hydrological control.

There has been on-going research into porous pavements which used a permeable concrete block structure (Pratt *et al.*, 1988; Pratt, 1989; Pratt and Hogland, 1990; Pratt, 1992). This structure was developed at Nottingham, where two experimental car park surfaces were laid. One site was at the Clifton campus, Nottingham Trent University, built in 1986. The ground conditions were not favourable for infiltration, but the structure had a large storage capacity (100 mm rainfall) which could cope with any excessive rainfall events. The dimensions of the car park were 40 m by 5 m, with the structure comprising of:

a) permeable concrete surface blocks (CeePy blocks);

b) 70 mm of crushed gravel, 2-10 mm size fraction;

c) geotextile;

d) 200 mm of sub-base stone, which varied between the bays and included gravel, blast-furnace slag, limestone and granite.

The structure was sealed at the base by an impermeable membrane, thus allowing the throughflow to be collected and analyzed (Mantle, 1987). The cost of construction (excluding the cost of the membrane) was £2300 for a car park with parking area for up to 16 cars, excluding some labour costs. This had a lower, and more favourable cost in comparison with a similar area surfaced with impermeable tarmacadam (Mantle, 1987).

The second site was built on a Nottingham City Council car park (Gill Street) in 1985. It had a similar construction to the Clifton structure except that the sub-base stone was limestone and the gravel above the geotextile was of a slightly smaller size fraction (2-6 mm). Infiltration rates for the block surfaces were tested in 1987 and was found to be in excess of 1000 mm h^{-1}. This rate had decreased to 100 mm h^{-1} by 1993 due to clogging, but the surface had not experienced any maintenance during the six years (Pratt, 1993; personal communication). The reduction in the infiltration rates was less than those described by Hogland (1990), who found a reduction from 720 mm h^{-1} to 64.8 mm h^{-1} after 4½ years.

Laboratory simulations on the permeable surface blockage was undertaken at Nottingham (Pratt, 1989). The laboratory simulations of the blockage mechanisms applied two sets of stormwater samples (the first being gully pot liquor containing inorganic and organic particles; and the second comprising liquor from the washing of the gravels). The laboratory data suggested that the sediment was transported throughout the whole gravel bedding layer, fanning out immediately below the infiltration inlets. Sediment concentrations were 0.95% sediment (by weight of the sample from the infiltration inlet) in the upper half of the infiltration inlet; 0.65% in the lower half; 0-0.5% in the top half of the bedding material; and 0.2-0.6% in the lower half. The "fanning out" was restricted to the bedding material above the geotextile. A model was produced which suggested that it was extremely difficult to block the infiltration inlet and that the bedding material would be the first area to fill.

Research results from these structures illustrated a decrease in discharge by at least 30%, mainly caused by initial loss (surface wetting etc). The rainfall loss was found to be increased by the use of different sub-base material, as well as by increasing the depth of the sub-base stone (Pratt, 1989). These systems were suggested to have an efficiency of intercepting stormwater for up to ten years (CIRIA, 1992, Vol.2). Stormwater quality was also seen to be enhanced due to pollutant retention within the structures.

The experience in the U.K. of this type of system has been limited and, as the CIRIA report (1992, Vol.3) suggested, there is a need for additional research to examine the long-term performance of these structures.

2.5 Summary.

From the literature, a number of advantages and disadvantages of using infiltration techniques have been identified and are summarised below;

Advantages:

a) attenuation of the storm hydrograph;

b) reduction in rainfall volumes reaching the sewer system;

c) reduction in pollutants reaching the sewer systems;

d) possible reduction in installation costs;

e) contained structural integrity after frost action;

f) elimination of vehicle hydro-planing;

g) reduction in land required to detain stormwaters;

h) partial return to "natural" hydrological conditions;

i) possible increase in groundwater recharge.

Disadvantages:

a) clogging, especially during construction;

b) installation costs may be higher occasionally, but this is site specific;

c) possible risk of groundwater contamination if the site has not been sufficiently surveyed;

d) restricted to low density traffic areas due to structural strength and clogging problems.

2.6 Areas identified for research.

Having examined a wide spectrum of research projects, it became obvious that most of the research had dealt with the hydrological performance of the permeable pavements as a 'black box' study, only measuring the input and output in a crude manner. To gain an improved knowledge on the hydrological performance of these structures, it was necessary to obtain detailed information on the hydrological processes and pollution/sediment retention mechanisms which were occurring within these structures.

Few of the research projects had emphasised the importance of evaporative losses from these surfaces. If these structures were to be used extensively as reservoir structures, a proportion of the water in the reservoir could be lost by evaporation. To understand the hydrological regime of these structures, evaporation, as well as rainfall input and discharge, should be examined in detail.

Clogging of the structures was also identified as a disadvantage, therefore, research was needed in order to ascertain the lifespan of the structures and the main areas of sediment retention within the structure.

Two areas were identified as lacking information in previous research projects:

1) Research on detailed hydrological performance, including information on evaporation amounts; and

2) Research on the clogging of the structures and the main areas of sediment storage.

Permeable pavement research was already established in the UK on a surface used for car parking purposes (Mantle,1987; Pratt et al., 1989; Pratt, 1989; Pratt and Hogland, 1990). Research had examined a permeable pavement car park structure which used concrete blocks as a surface and illustrated the positive effects, both for stormwater runoff reduction and for sediment retention. In order to gain more detailed information on the hydrological performance of this permeable pavement, a car park structure similar to the one used at Nottingham was chosen for analysis. The same block surface was chosen because it used concrete blocks which were specially designed to allow for infiltration into the bedding material. This surface was also chosen because previous research (Van Dam and Van deVen, 1984) illustrated that a block surface increases the possibilities of surface water storage by surface moistening, in comparison with other surfacing materials (eg concrete tiles).

The previous research at Nottingham was a "black box" study and it was felt that more detailed information on the hydrological performance of the structure could be obtained if the structure was examined on a small size, but using a full scale model and under controlled laboratory conditions.

Chapter 3 - Experimental Design.

3.1 Introduction

The intention of this research project was to identify and measure the hydrological processes operating within a model car park structure. The processes that were considered essential for measurement and analysis were:

1. Rainfall intensity, duration and frequency;
2. Discharge rates and amounts;
3. Evaporation rates and amounts;
4. Retention rates and amounts.

The large-scale experiments performed by Mantle (1990) on similar car park structures yielded information on the rainfall input, the drainage output and a calculated retention, but these latter data were not adequate to provide details of processes, such as evaporation, which occur continuously during and after a rainfall event.

Two types of data were required in order to calculate and quantitatively assess the hydrological processes which were occurring in the model car park structures:

a) detailed sequential rainfall input to and discharge from the model. This information was required in order to produce hydrographs and to allow calculations to be made of retention within the structure;

b) data giving quantitative changes in the water volume (or weight) stored in the model structure before and after rainfall events, thus allowing the evaporation rates and amounts to be calculated.

There were three types of equipment which were designed and developed in order to gather the required information:

1) the model structure;
2) a weighing apparatus;
3) a rainfall delivery system.

Equipment was also set up to monitor potential evaporation from an open water body with the same surface area as the model structure; and to provide a continuous measure of relative humidity and temperature.

The first problem was to develop a model car park structure on which rainfall could be applied and the rates of actual evaporation, retention and discharge monitored. The second set of equipment, i.e. the weighing apparatus, allowed the model car park to be weighed, which meant that quantitative measurements of actual evaporation and retention could be obtained. The rainfall delivery system allowed controlled rainfall to be applied to the surface, with both the input from the simulator and discharge from the base of the model being monitored at the same time by electronic weighing balances.

Section 3.2 outlines the equipment used to collect the data which were required to measure the factors outlined above. This is followed in section 3.3 by a discussion of the experimental procedure.

3.2 Experimental Equipment

3.2.1. Structure of the simulated model car park.

Earlier research by Mantle (1990) concentrated on the hydrological regime of a full-scale car park surface of some 200 m^2. A variety of sub-base stone types were examined, but the surface blocks and bedding material (pea gravel) remained the same for all areas whatever the sub-base. This research project is an extension of this previous research and was designed to gather more detailed information on the hydrological regime of the surface structure, i.e. the surface blocks and bedding material. During experimentation, the sub-base stone layer was not modelled because previous research had already examined this component of the porous pavement (Pratt *et al.*, 1988). This project was concerned more with processes, such as surface evaporation, and changes in the hydrological regime due to surface clogging.

A model permeable pavement structure was designed which represented the previous full-size car park surface at a laboratory scale. This model car park structure had to be of a design which would enable accurate measurement of water input, drainage output, retention and evaporation. The chosen design, based on a box-like structure, was constructed in order to fulfil the following requirements:

1) to be large enough to be representative of macro-processes operating on the car park structure;
2) to be small enough to be weighed;
3) to be able to take a sufficient depth of bedding material and the surface blocks for the designed experiment;

4) to allow for the unimpeded discharge of percolating water from the base of the structure.

The adopted design, illustrated in Figure 3.2.1, involved a plastic vacuum-moulded box, made from clear PVC, with internal dimensions 600 by 600 mm. The physical structure was divided into two zones. Zone 1, 190 mm deep, allowed adequate space for the constituents of the car park structure. Zone 2, an inverted pyramidal design, allowed for the rapid drainage of percolation from the base of the car park structure and discharge to a collection point below the model.

There were four major components in the simulated car park:

1) Concrete surface blocks (CeePy blocks, specifically designed for the original full-scale car park surfacing (Mantle, 1987)):
2) Bedding stone, mainly pea gravel and crushed limestone;
3) Geotextile - Terram 1000 (trade name);
4) The base support of stainless steel mesh.

3.2.2. The Concrete Blocks.

The concrete blocks, which were placed at the surface of the model structure, had an unusual design in that 15% of the rectangular surface area was open and acted as infiltration inlets which increased the rate of water entry to the sub-base areas. A second important design feature was that the blocks had raised circular areas which reduced compaction (in the prototype) of the gravel in the 'open' areas by car wheels. The blocks were made from a mixture of cement, aggregate and pulverised fuel ash.

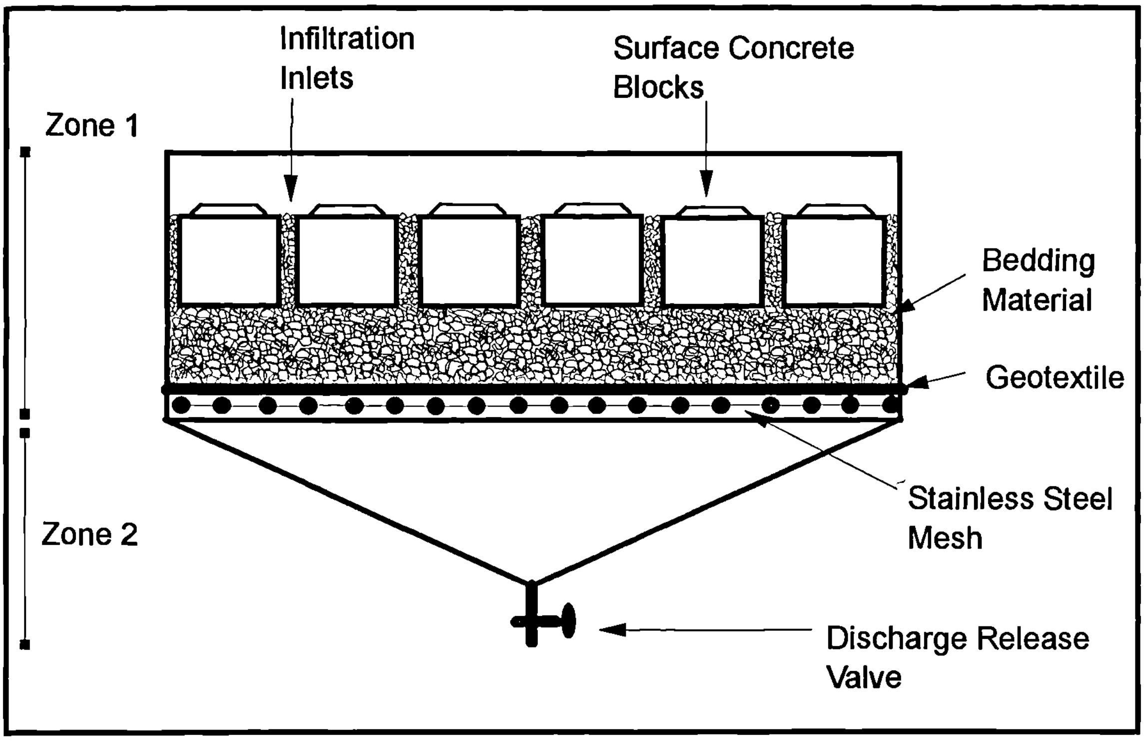


Figure 3.2.1. A diagrammatic representation of the model car park structure.

The latter was thought to influence the density and the water absorption capacity of the blocks, which was found to be 4-6% of the oven dry block weight. Figure 3.2.2 and plate 3.2.1 illustrate the dimensions of the blocks.

3.2.3 The bedding stone

The bedding stone was predominantly pea gravel which was sieved into various grain sizes, ranging from 1-10 mm. In some experiments a crushed limestone with a grain size of 5-10 mm was used. The bedding material was placed directly below the concrete blocks and also in the infiltration inlets, once the surface blocks had been laid in a herring-bone pattern.

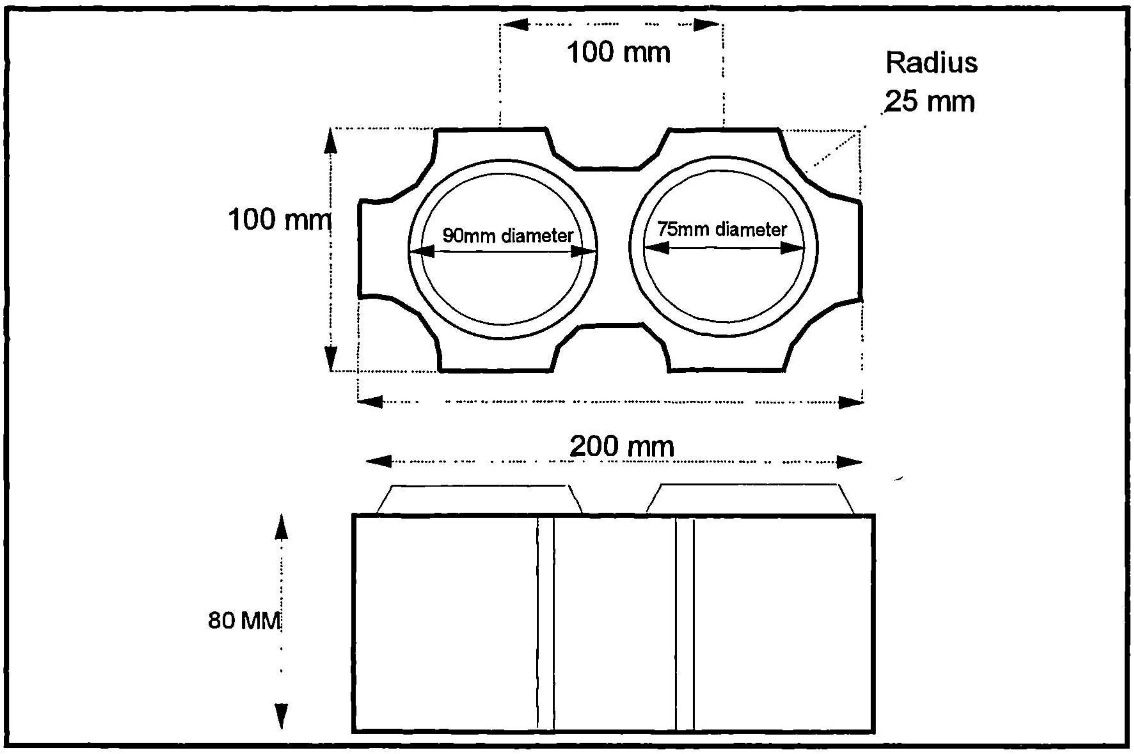


Figure 3.2.2. **The dimensions of the surface concrete blocks. The blocks are laid in a herring bone fashion.**

Plate 3.2.1. **The concrete surface block.**

3.2.4 The geotextile

The third component was a geotextile, "Terram 1000". The geotextile consisted of 70 % polypropylene and 30 % polyethylene. It had chemical resistance to all naturally occurring alkalis and for acids greater than, or equal, to pH 2; and it was "unaffected by bacteria" (Terram 1000 brochure). The tensile strength of the textile was stated to be 1.6 KN m^{-1} for a 200 mm width strip. The mean pore size was 100 microns and the geotextile had a permeability of 50 l m^{-2} s^{-1}.

3.2.5 The base support

The fourth component was the stainless steel mesh, which had the function of supporting the model car park structure. Stainless steel was chosen because it suffered very little from corrosion and would, therefore, retain its strength and not interfere with any water quality analysis.

The design of the car park structure fulfilled the requirements identified in section 3.2.1. The dimensions were small enough to allow for the full-scale model structure to be weighed using a specially designed balance, but were considered large enough to be representative of a car park structure in terms of hydrological performance.

The volume within the box was large enough to take the required depth of material and the design also allowed for the rapid drainage of percolating water, thereby reducing inaccuracies which might have resulted from the ponding of water below the base support. The next important issue was to choose the box components to be used in the model car park constructions during the hydrological simulations.

3.2.6 The variations in box components

From preliminary hydrological experiments (Chapter 4) on the individual structural components in the model, it was shown that the concrete blocks and bedding material exhibited differing retention and evaporation rates. Furthermore, there were significant variations in the above processes depending on the size of bedding material used. It was concluded that a number of experimental boxes should be constructed with varying structural components (all boxes contained the steel mesh and geotextile). Table 3.2.1 illustrates the box components. If the rainfall event was constant for all boxes, then the variables (box structural components) could be assessed with regard to their impact on retention, drainage and evaporative processes. Box 5 was regarded as the control box since the components were the same as those used to construct full-scale surfaces.

Table 3.2.1 Components of the model car park structures.

Experiment Box Number	Type of Bedding stone	Depth of Bedding stone (mm)	Grain size of Bedding stone (mm)	Concrete Blocks present
1A	Block only			Yes
1B	Pea Gravel	50	1-10	No
2	Pea Gravel	50	1-10	Yes
3	Pea Gravel	30	1-10	Yes
4	Pea Gravel	70	1-10	Yes
5	Pea Gravel	50	5-10	Yes
6	Pea Gravel	50	3-5	Yes
7	Pea Gravel	50	1-3	Yes
8	Pea Gravel Limestone	25 25	5-10	Yes
9	Pea Gravel Limestone	30 40	5-10	Yes
10	Limestone	50	5-10	Yes

3.2.7 Design of Balance equipment.

The design of a device which was capable of weighing the model car park structure was one of the most complicated practical features considered in the experimental design. An electronic load cell could not be used since it would not give the accuracy that was required (ie. total evaporation from the surface may be as little as 20 g day^{-1} with the box having a mass in excess of 70 kg). After considering several possibilities, a knife-edged balance was selected as the most effective method for obtaining data on the changing weight of a model structure.

The design was based on a beam balance and incorporated three knife-edge points which were intended to reduce friction and increase the accuracy of weight measurement. Figure 3.2.3 illustrates the design of the balance. The balance was attached to a jib arm extension which fitted a pedestrian-operated hoist with an adjustable crane arm (plate 3.2.2). The operator could raise or lower the balance when required and, because the balance was mobile, move the balance along the row of model car park structures when necessary.

3.2.8 Balance Weighing Procedure.

Data collected from the balance were in the form of differing counterbalance weights required to compensate for rainfall inputs or evaporative losses from the model structures over time. The difference between consecutive readings gave water gain or loss which, in theory, allowed calculation of water retention within the model car park structure.

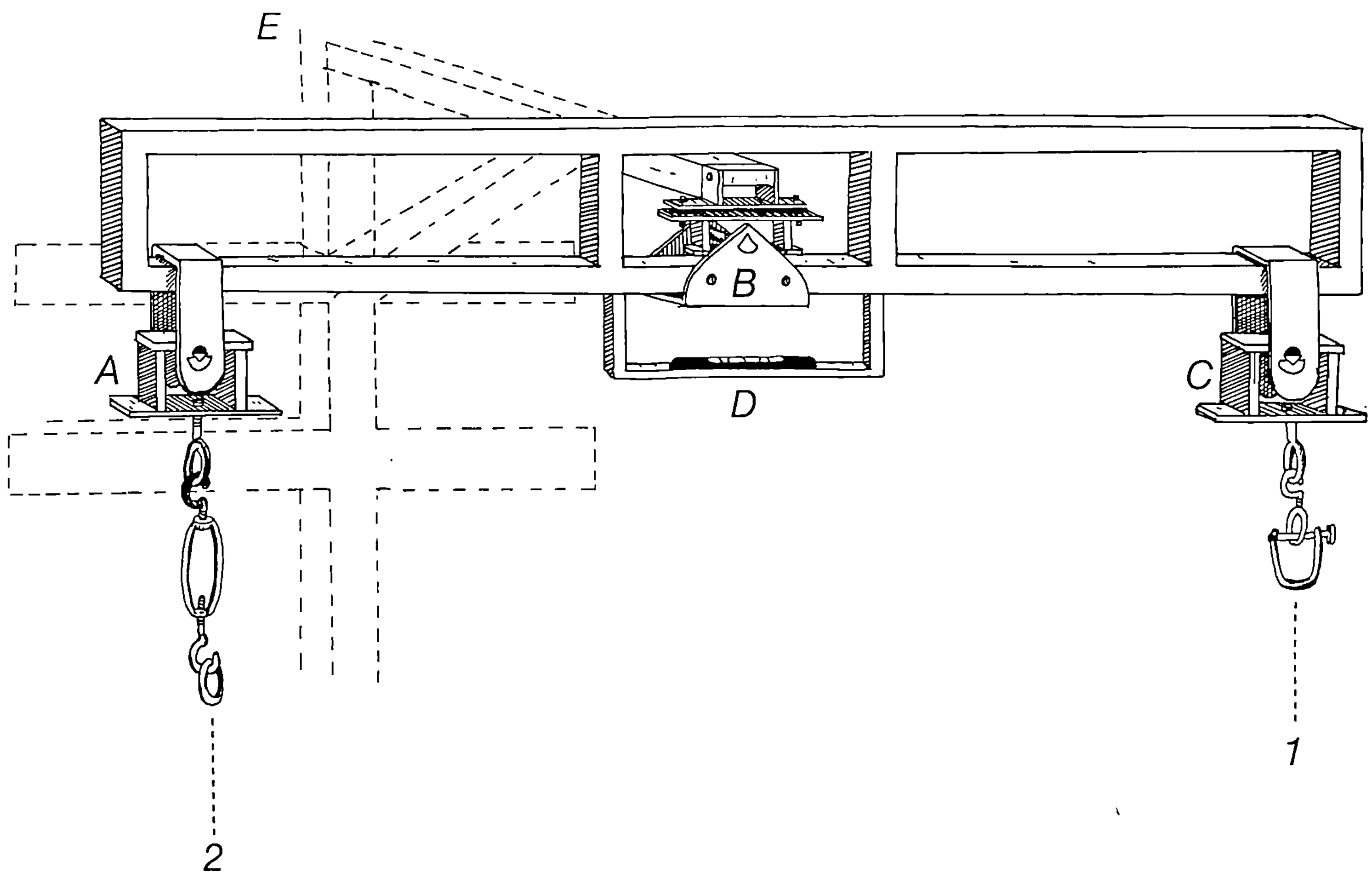


Figure 3.2.3.The design of the Three Knife Edge Balance used to weigh the car park structures.
A, B, C = Knife edges, D= Spirit Level, E= Crane arm attached to pedestrian operated hoist, 1= Attached to Car Park Structure, 2= Attached to the counter balance and adjustable weight.

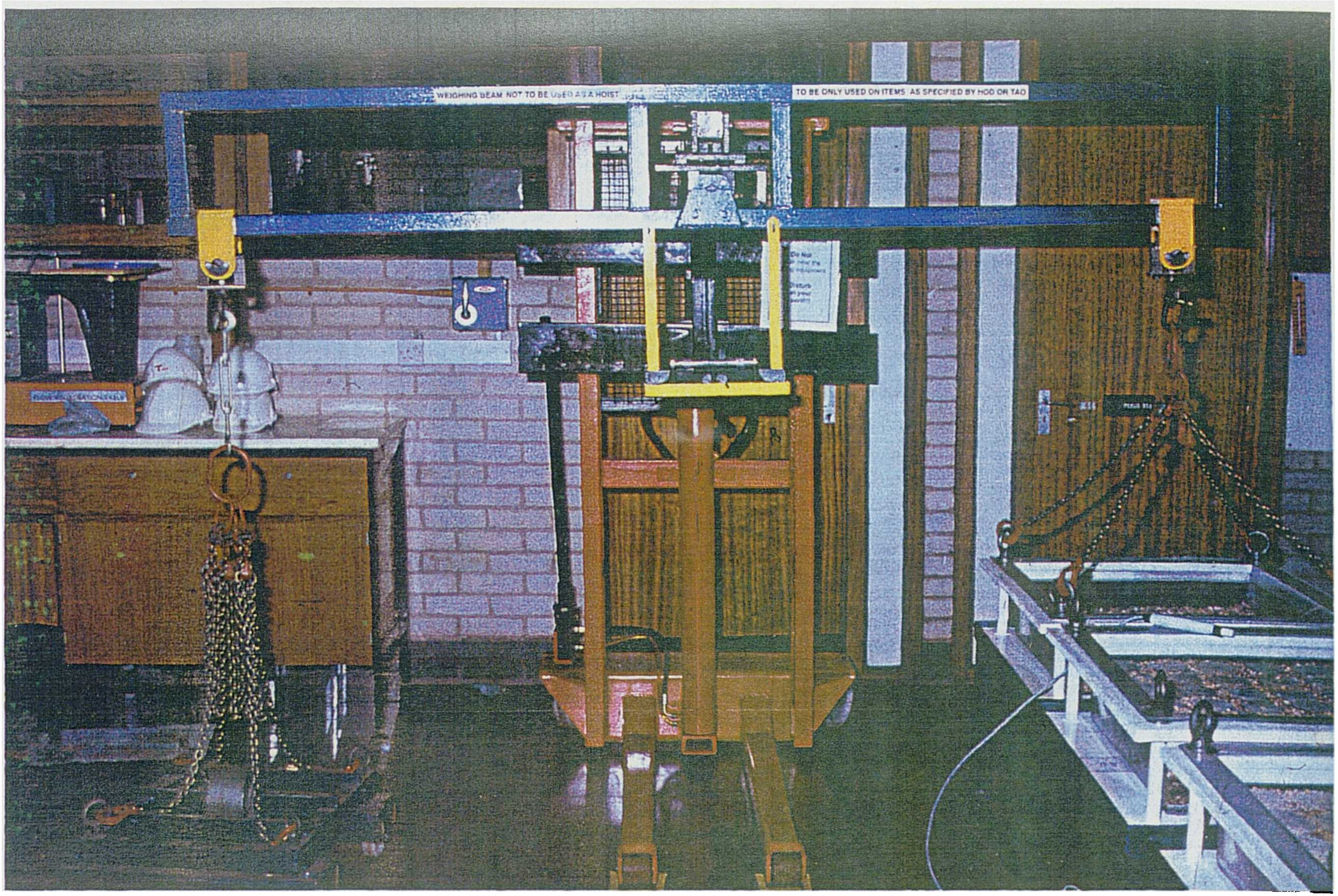


Plate 3.2.2 The knife edge balance attached to the adjustable counter weight and the model car park.

At the beginning of each experiment, the model box was weighed and the weight was then referred to as the "original box weight". In order to perform this measurement, chains were attached to the box and then, using the hoist, the box was raised clear of the base support. Changes were made to the counterbalance weight in order to bring the balance to equilibrium. The weight was recorded when an air bubble was centred on the spirit level (see Figure 3.2.3 (D)).

Once rainfall had occurred and drainage ceased, subsequent changes in counterbalance weights were used to estimate water retention changes due to evaporation. During the preliminary hydrological studies, it was noted that lifting the box immediately after rainfall disturbed a portion of the water retained by surface tension; a situation that would not occur in reality. In consequence, further weighing was only undertaken after a 24-hour delay, which allowed sufficient time for drainage to occur.

Calibration of the Counter Balance.

The balance was designed to give a high degree of accuracy, incorporating three knife-edge points (hardened steel edges), in order to reduce friction. Care had to be taken to ensure that the balance beam was parallel to the pedestrian-operated hoist and that the knife-edges were not in contact with the cage in which the knife groove was located. Any contact with the holding cage would bias the balance readings. Consequently, before weighing a box structure, several checks were made of the hoist equipment to ensure accuracy.

At the beginning of the experimental phase, the counter balance was checked for it's level of accuracy. Following previous counterbalancing of the weighing device with one model box, an unknown weight was placed on the model box and the counter balance weight was loaded to achieve equilibrium. The accuracy of the weighing device was shown to be 5 g in 100 kg, which could be increased if the distance from the fulcrum of the counter weight was decreased. This is a high degree of accuracy, as it is equivalent to measuring as little as 0.014 mm of rainfall on the model car park surface. Over time, the accuracy of the balance was found to decrease. This was due to wear on the knife-edges. Over the two years of the experiment, this resulted in a reduction in accuracy from 5 g to 30 g in 100 kg i.e. from 1 in 20000 to 1 in 3333 (the balance was used daily).

3.2.9 Design of the rainfall simulator.

In designing the rainfall simulator, the intention was to produce a "near-natural" rainfall. This meant that the manner in which simulated rainfall was applied to the model car park had to imitate natural rainfall i.e., there had to be droplet formation. The design had to allow for rainfall volume, intensity and duration to be controlled to suit the experimental requirements.

After an examination of various rainfall simulator designs (e.g. Selby, 1970; Savat, 1981), one was selected which could be modified and further improved (Bowyer - Bower and Burt, 1989) for the purposes of this experiment. The design allowed for varying intensities, durations and resultant volumes of rainfall to be applied to the model car park structure. A delivery system for the water was developed, replacing the previously reported constant head supply system. There were two main parts to the rainfall simulator, namely:

1) the rainfall simulator box;

2) the water delivery system.

3.2.10. The rainfall simulator box.

Figure 3.2.4 illustrates the design of the rainfall simulator box. The box comprised two layers of 10 mm thick, clear PVC of 640 mm square sides. The top layer had four air release valves which were manually controlled and were used to remove air trapped in the simulator box. This was necessary if the pressure was to remain constant during the 'rainfall event'. Below this layer was a 10 mm edging strip of PVC, which created a gap between the top and the base layers of PVC which was filled with water.

The bottom sheet of PVC was drilled with holes, through which Tygon tubing (trade name of Cole Palmer) with an internal dimension of 0.7 mm and an external dimension of 2.3 mm was threaded. The Tygon tubing was cut to lengths of 15 mm. Before the Tygon tubing was threaded into the pre-drilled holes, fishing line (thickness 0.65 mm and 25 mm long) was inserted into the tubes. The end of the fishing line inside the simulator box was crushed to keep it in place. The purpose of the fishing line was to produce a point on which rain droplets could form and fall from the simulator. The fishing line extended below the Tygon tubing by 10 mm, allowing the droplet to fall freely. The rainfall simulator box had holes drilled at intervals of 28 mm in rows. On the lower plate of the rainfall simulator there were also four inlet points where the pressurised water from the supply entered the gap between the PVC sheets. Once the

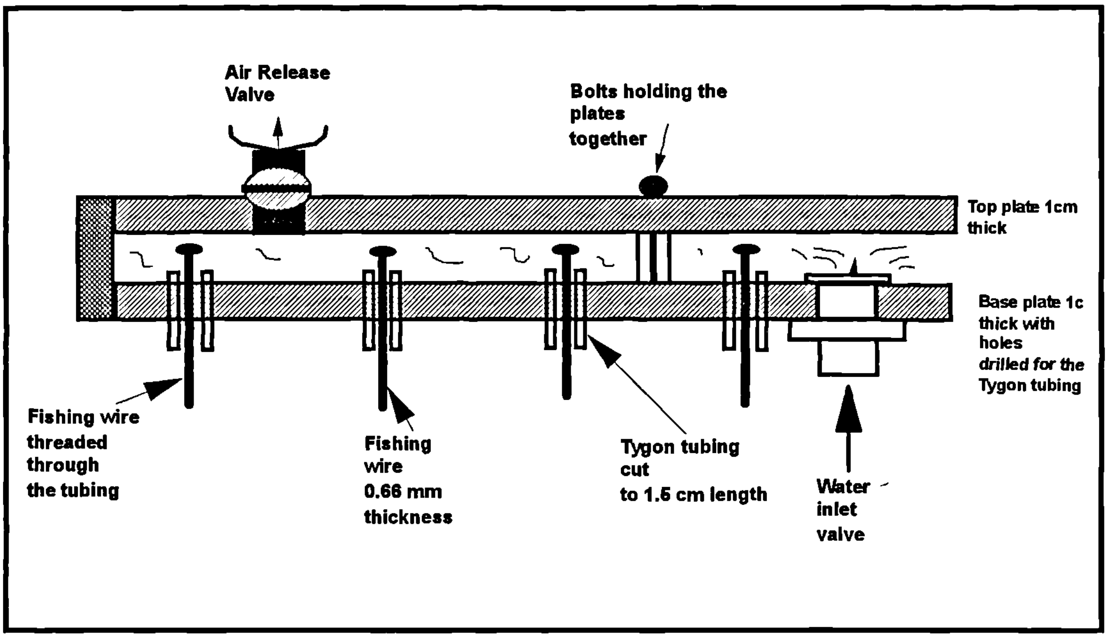


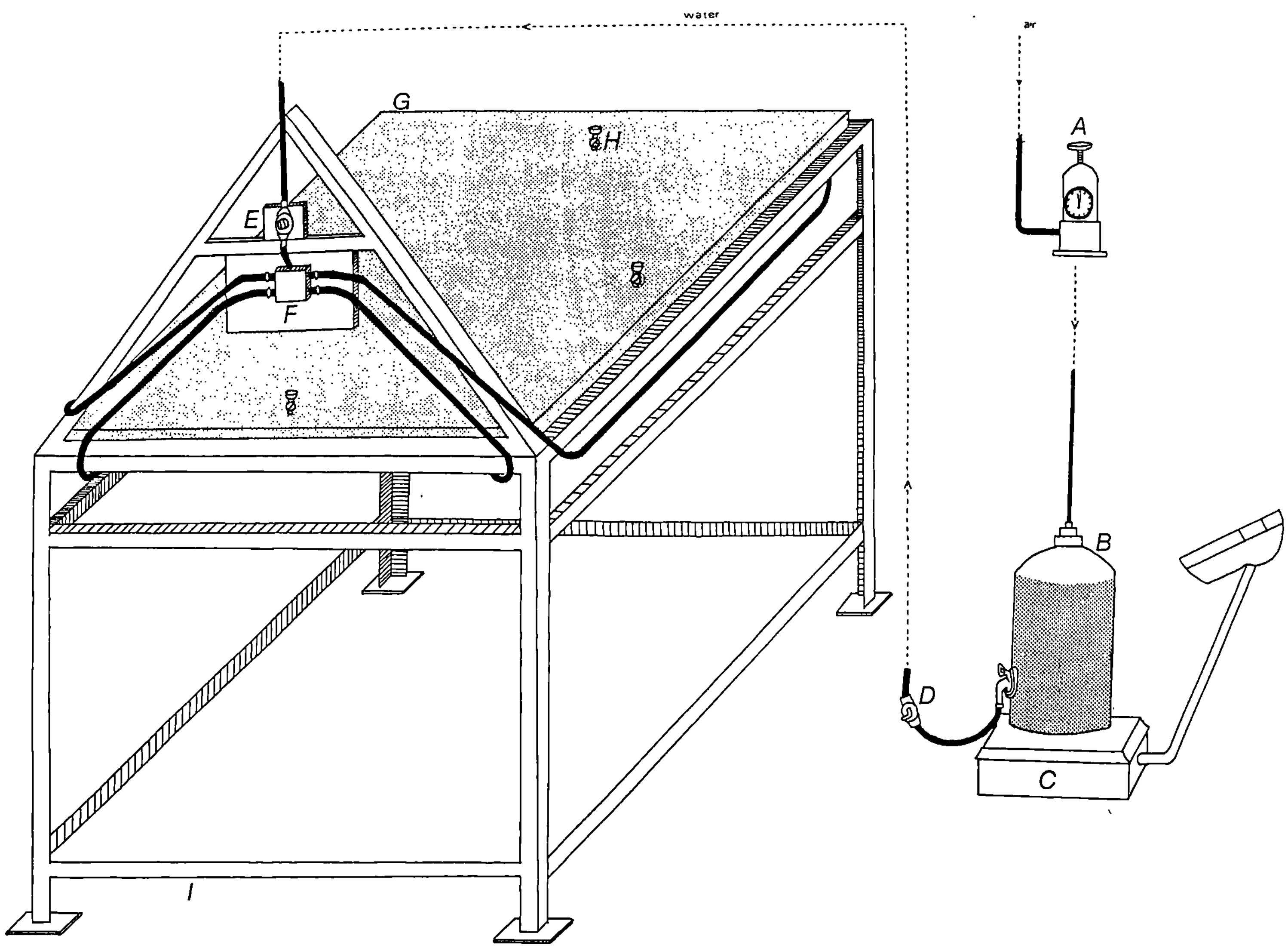
Figure 3.2.4. Section through the Rainfall Simulator box, illustrating the movement of water into and out off the box, via the Tygon tubing.

three PVC plates were bolted together, the simulator could be made air-tight with silicon sealant. The rainfall simulator had PVC plate dimensions which were the same as the surface area of a model box, which meant that the rainfall produced would fall only onto the model car park structure. It could be moved from model box to model box simply by guiding the mobile frame over the top of the boxes (see plate 3.2.3).

3.2.11. The water delivery system.

Figure 3.2.5 illustrates the design of the pressure system. A high pressure air supply was directed into a 25 litre pressure barrel. The pressurised air was introduced into the barrel through a regulating pressure gauge (see Figure 3.2.5.(A)) which allowed the pressure to be modified as necessary. At the start, the barrel was full of water and the

Plate 3.2.3. The Rainfall Simulator placed over a model car park structure.



<u>Figure 3.2.5.</u> A diagrammatic representation of the water delivery system.
A= Pressure Valve, B= Pressurised barrel, C= Balance (A), D= Water control valve, E= Second pressure valve, F= Five-way manifold, G= The rainfall simulator box, H= Air release valves.

high pressure air supply was turned on and a constant pressure was established, forcing the water to enter the rainfall simulator box.

As the rainfall simulator began to fill with water, any air inside was released through the air release valves (see Figure 3.2.5 (H)). Once all the air was released, and the pressure had reached equilibrium, the rainfall simulator was ready for operation. The rainfall simulator had a splash guard which ensured that all the rainfall landed upon the model car park surface.

The design of the system incorporated a pressure valve which allowed the operator to increase or decrease the pressure within the system. Various rainfall intensities could be produced: any change of intensity was rapid and involved no manual effort. By simply turning a valve on the tube delivering the water to the PVC simulator box (or for large intensity changes also adjusting the air pressure valve to the water reservoir), it was possible to vary the intensity from 1 mm h^{-1} to 100 mm h^{-1}. The use of this pressurised system increased the versatility of the rainfall simulator. In the laboratory the air was supplied from a central compressor.

Electronic balances were located beneath the pressurised barrel and the collecting bucket at the base of a model box structure. To achieve a controlled intensity, the water loss (g) from the pressurised barrel supplying water to the simulator was controlled until the constant loss per unit time was reached, i.e. a loss of 90 g per minute was equivalent to a constant rainfall intensity for a 15 mm h^{-1} rainfall event. The accuracy of the rainfall intensity depended on the ability of the operator to control the water supply valves.

Periodically, the rainfall simulator had to be dismantled and the Tygon tubing replaced. This was mainly due to blockage caused by calcite deposits from the hard water in the mains supply. If this maintenance was not carried out, the pressure within the simulator box would have had to be greater in order to produce the required intensity of rainfall. The increased pressure occasionally caused the Tygon tubes to be blown out. By periodically changing the tygon tubing (every month) and by using only distilled water, the number of malfunctions was reduced.

3.2.12 Calibration of the Rainfall Simulator Equipment.

The rainfall simulator was checked for it's accuracy of water delivery. This was carried out on an empty box, which would contain a model car park structure. Two electronic balances were used: Balance (A) (measuring range 40,000 g x 0.5 g increments) which was situated beneath the pressurised barrel; and Balance (B), which was located beneath the collecting device at the base of the structure. After three rainfall events, balance (A) and balance (B) showed a difference in readings, with Balance (B) always showing lower readings (when input was expected to equal output) of 21 g, 24 g and 19 g, respectively. This was an average of 0.4 % difference between the two balance readings for three rainfall events of 3 litre volume input with durations of 10 minutes.

The differences could not be attributed to evaporation since the length of the experiment was only 10 minutes. Therefore, the difference had two possible explanations:

1) the model box did not drain completely;
2) the differences were due to inaccuracies in the balance readings.

The latter explanation was eliminated from the possibilities since both balances were checked for accuracy by calibration testing of each balance. Both balances read the same, for the same known weight, after several repeat tests. As a result the difference was attributed to the box not draining completely, which was also visible, on inspection, after rainfall simulation events. An error of 0.4% was considered acceptable within the overall experimental design.

3.2.13 Rainfall Intensity - sources of error.

The main source of error associated with the rainfall simulator was its sensitivity to changes in pressure from the high pressure air supply. As a result it was extremely difficult to maintain a constant rainfall intensity during a rainfall event. There were three reasons for this:

1) The pressure valve controlling the pressure entering the pressurised barrel was somewhat crude, having a range from 0 - 40 psi. The pressure required to create the desired rainfall events ranged between 0-5 psi. It would have been preferable to have a more precise valve. Unfortunately, the cost of such a valve was in excess of available funding. The solution chosen in order to enhance the accuracy was to add a second valve before the five-way manifold, allowing the pressurised water flow to be reduced or increased when required.

2) The second reason for the variations in intensity, was that, after a length of time (approximately one month), the Tygon tubing became partially blocked. This meant that the pressure entering the five-way manifold had to be increased in order to maintain the required intensity. Unfortunately, this had the added problem of creating greater pressure within the simulator rainfall, which occasionally led to the blow-out of Tygon tubes. This "blow-out" produced

some increase in the rainfall intensity, but the problem was always rectified quickly since the simulator was continuously monitored during a rainfall event.

3) In order to produce a near constant rainfall intensity, the valve controlling the water entry into the rainfall simulator had to be manually manipulated. The rainfall intensity during the initial stages of the rainfall event was variable due to the operator attempting to produce the required constant intensity. Figure 3.2.6 provides an example of the variations during an actual rainfall simulation. It can be seen that rainfall intensity values vary the most during the initial and later stages of the simulation.

The variation in intensity was identified as an important source of experimental error if the experimental method required an exact rainfall intensity. These experiments required a known volume of rainfall to be applied over a pre-determined time period (30 minutes, 1 and 2 hours), as the examination of the hydrological performance was mainly restricted to discharge, retention and evaporation after a rainfall simulation. The mean rainfall intensities for thirty rainfall events were examined in detail and are given in Table 3.2.2.

Runs 1, 2 and 3 were designed to have a 15, 30 and 7.5 mm h^{-1} rainfall intensity, respectively. The mean value for each Box and run was calculated from intensities measured every 30 seconds over the duration of the rainfall simulation. The results indicated that the shorter the rainfall simulation, the greater the error in maintaining a constant intensity, but if the rainfall duration is greater than 1 hour, the error in mean intensity is lower.

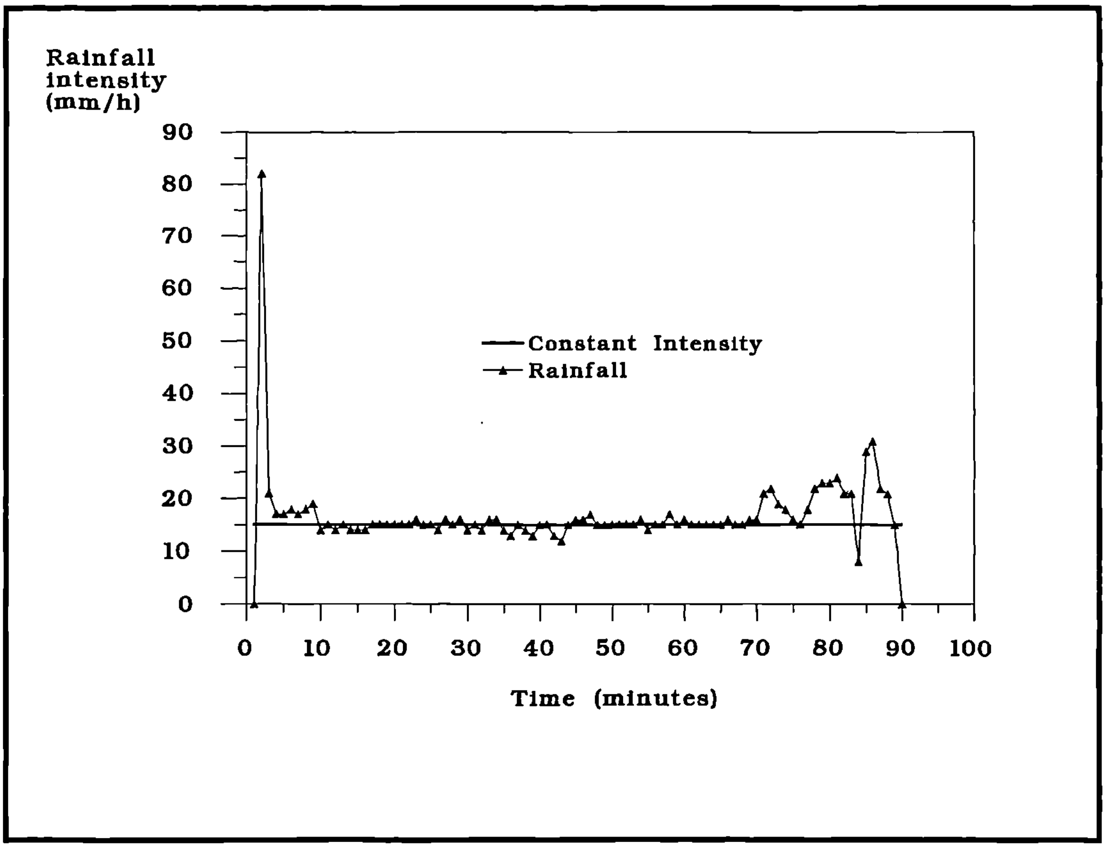


Figure 3.2.6. **The variations in rainfall intensity.**

Table 3.2.2 The mean rainfall intensity over 30 rainfall simulations.

Box number	Mean rainfall intensity ($mm\ h^{-1}$) during Run 1 (duration 1 hour)	Mean rainfall intensity ($mm\ h^{-1}$) during Run 2 (duration 0.5 hours)	Mean rainfall intensity ($mm\ h^{-1}$) during Run 3 (duration 2 hours)
One	21.95	29.53	7.57
Two	16.64	28.81	7.85
Three	14.20	28.80	7.58
Four	15.55	24.70	7.55
Five	13.26	25.89	7.67
Six	15.06	35.33	8.79
Seven	15.12	29.78	7.66
Eight	14.52	45.58	7.40
Nine	14.39	29.70	7.78
Ten	15.20	24.62	7.52

3.2.14. Design of Evaporation Pan.

The equipment was designed to allow measurements of actual evaporation from the models by weighing each car park structure repeatedly through time. In order to understand more clearly the evaporative processes, measurements of actual evaporation were required to allow for an assessment of the quantitative differences between evaporation rates for an open water body (under similar laboratory conditions) and for the model car park surfaces. An empty model box with the same surface dimensions as the model car park structures was chosen to act as an evaporation pan. One of the eleven boxes was sealed at the base and filled with water. A thimble micrometer had a brass extension fitted on to the moveable section, which was connected via a terminal to an ammeter. The brass extension was filed to a point in order to reduce interference created by a large surface area on the contact point (see Figure 3.2.7).

A secondary brass rod was attached to a PVC holding device and was connected via another terminal to the ammeter. The PVC holding device was secured to the edge of the PVC evaporation box. The depth of the water was measured by lowering the thimble micrometer's brass extension to the water surface. When the surface was touched, the pointer on the ammeter displayed the contact and the reading on the micrometer was taken. This procedure was repeated for 100 days. The amount of evaporation was calculated by finding the difference between the original water depth reading on the micrometer and a following reading of the water level, 24 hours later. The micrometer could detect variations in water depth to an accuracy of 0.5 mm. The evaporation pan was periodically refilled with water and the calculations modified accordingly.

3.2.15. Equipment used to monitor evaporation from the concrete surface blocks - the "wick" effect.

The concrete block surface, situated at the top of the car park structure, was the surface from which water was lost by evaporation. Preliminary analysis of block absorption and evaporation rates indicated the pattern of water uptake and release (Chapter 4). However, the methods of testing reported here were not, in reality, similar to conditions during or after a rainfall event. Another experiment was designed which would allow evaporation from the surface of a single block to be monitored (see Plate 3.2.4). The block was sealed in an air tight container so that only the top surface was exposed to the air, from which water could be released by evaporation. Any vacuum (by suction created by evaporative losses) in the container surrounding the block and holding the water, was accommodated by the presence of a latex seal which had been pierced by a pin.

The latex seal would allow air to enter the water container and would minimise any evaporative losses from the water in the box except via the block surface. Any change in weight of the sealed box was assumed to be due to evaporation from the block surface only (see Plate 3.2.5).

The experiment was designed to examine the "wick" effect of the block i.e. the water movement up and through the block. An oven dry block was placed in the sealed container and water was introduced to the base of block to a depth of 20 mm. The block was allowed to settle for a day. Changes in the total weight of the equipment was monitored daily as evaporation occurred.

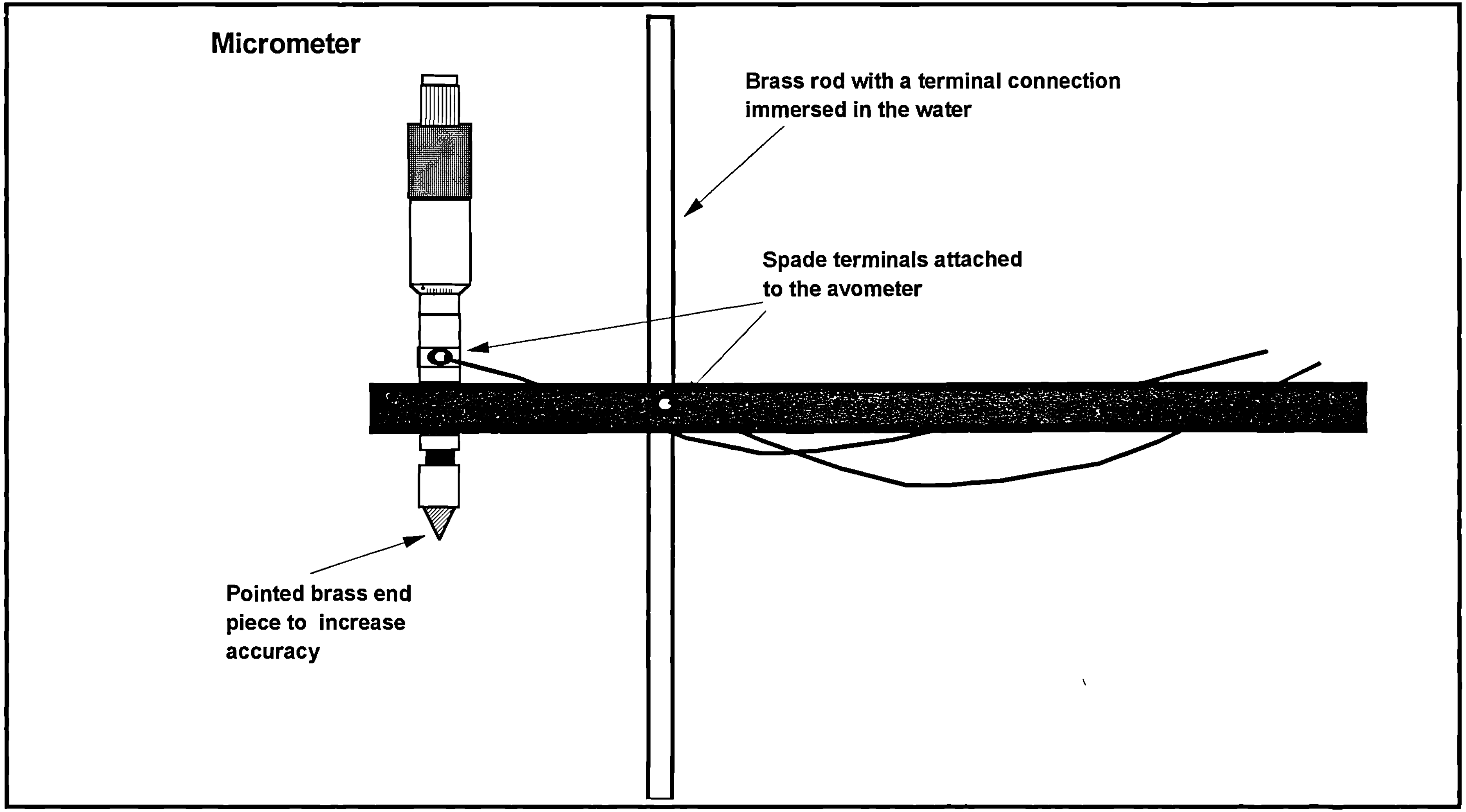


Figure 3.2.7. The thimble micrometer used to calculate potential evaporation. The micrometer is lowered to the surface of the water until it makes contact. Once contact has been made the voltage is conducted via the water and a response can be seen on the avometer.

3.2.16. Equipment used to measure humidity and temperature.

To examine the influence of humidity and temperature on evaporation rates occurring on the car park surfaces, measurements of humidity and temperature were taken during experimental simulations. To monitor humidity, a hygrometer probe was used (model MP-100 F Campbell Scientific). This probe had a measuring range for relative humidity of between 0-100 % and for temperatures between -40 to 60 degrees centigrade. The measurements of temperature and humidity were recorded every hour and stored in a 21X Campbell Scientific data logger.

Measurements of temperatures close to the experimental car park surfaces were also required. These were obtained by the use of thermocouples which were placed on some block surfaces. These were attached to the surface of the blocks with Araldite resin.

3.2.17. Computer Equipment and data loggers.

The equipment developed was expected to generate a great deal of data which would require computer processing. The counter balance and box weight readings were manually recorded and then processed by computer. Figure 3.2.8 illustrates the computer and data logger equipment which were used to collect data from the various monitors and balances. The computer terminal was linked to the data loggers by an SC23A interface. Using a computer package called PC208 (Campbell Scientific), the data loggers could be programmed to record data at the required time intervals. This necessitated special programs to be written which are listed in Appendix D.

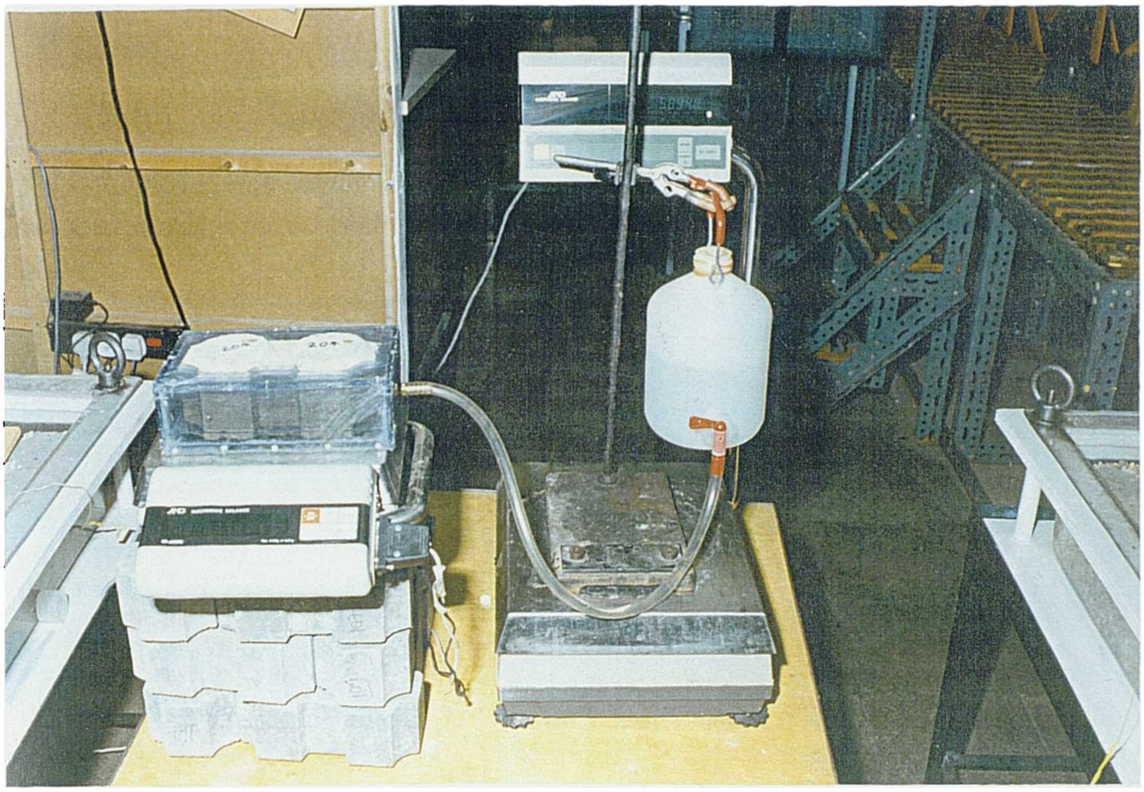


Plate 3.2.4. **The equipment used to monitor the "wick" effect by the surface blocks.**

Plate 3.2.5. **The surface block in a sealed container.**

3.2.18. The CR10 Data logger.

The CR10 logger was used to control the generation of data from the two electronic balances via an RS232 interface. The two balances recorded the following:
Balance A - positioned beneath the pressurised water barrel, data on the loss of water from the barrel was recorded (in grams) at 30 second intervals; Balance B - positioned beneath the device collecting output of percolating water from the car park structure, the weights of drainage from the boxes were recorded (in grams) at 30 second intervals.

3.2.19 The 21X Data Logger.

There were four 21X data loggers used during experimentation. One was programmed to collect relative humidity data every hour. The other three were used to gather surface temperature readings using the thermocouples attached to the surface of the boxes, again at hourly intervals. The computer programmes controlling these data loggers are also given in Appendix D.

Data generated by the data loggers were periodically down-loaded on to the computer. Using PC208, they were transferred into "As Easy As" (IBM program) and then into a Microsoft Works (for Windows) spreadsheet, where further calculations could be performed.

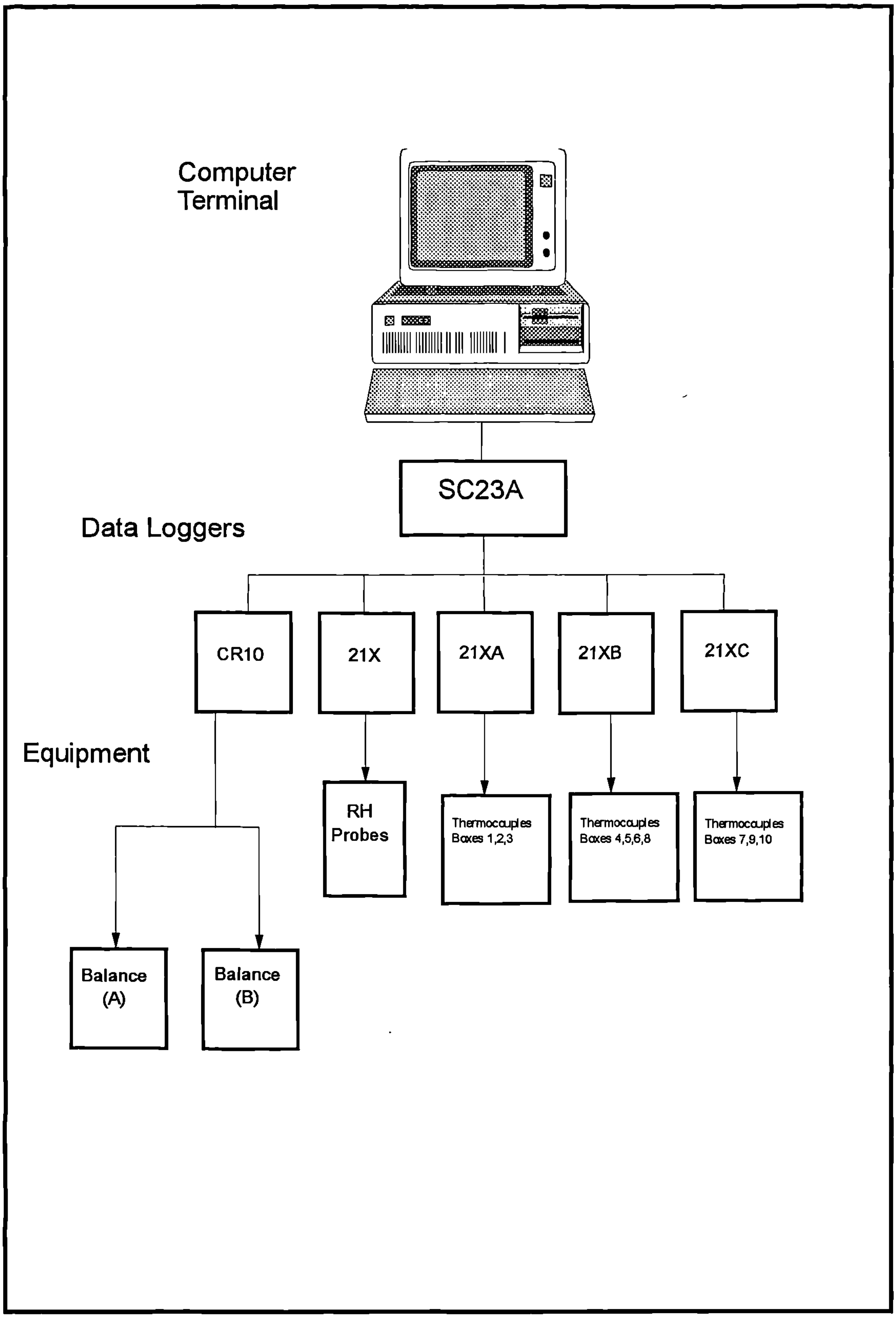


Figure 3.2.8 **A flow diagram schematically representing the equipment and their associated data loggers.**

3.3 Experimental Procedure

The previous section described the equipment developed to obtain data on the hydrological processes operating within the model car park structure. The following section describes the experimental procedure.

3.3.1 Box Component Experiments.

The first experiments undertaken were basic hydrological tests on the surface blocks, bedding material types, and varying materials with differing grain sizes.

Concrete Surface Blocks

A sample of 20 blocks was oven dried (at 40 °C) for three weeks and then weighed after standing in the laboratory for one week. They were placed in a tank of water and periodically taken out for weighing. This continued for 12 days until water absorption by the blocks was negligible. The experiment gave data on rates and the total amount of water absorbed by the blocks.

Evaporation from the concrete blocks was measured from the same sample as above. The blocks were allowed to dry in the laboratory (temperature was 16-18 °C). The weight of each block was recorded at hourly time intervals during the first 10 hours and then daily over the next 21 days.

Bedding Materials.

A selection of bedding materials used in the boxes in the hydrological experiments (see Table 3.2.1) were chosen from washed, oven dried (at 40 °C) samples. The samples were placed in containers of known volume, weighed and then saturated with water. The samples were allowed to drain for one hour, the base was sealed and the weight was then recorded. This gave information on bedding material retention. The same samples were then weighed every hour for 10 hours and then 62 hours later. This provided information on the short term evaporation rates from varying bedding materials. These experiments were simple but, as will be shown in Chapter 4, they provided vital information that could be used to explain and predict hydrological response to the rainfall input.

3.3.2 The Hydrological Experiments.

The boxes were constructed with laboratory air-dry materials (the individual box components are given in (Table 3.2.1). The long-term water content in the air-dry components provided a datum for all retention experiments. The water content of the blocks and gravels at this point was negligible (less than 0.5% of the block weight) and it was considered that this would be of the same magnitude as for the structural components used to construct any full-scale structures in the field.

Initially, each box was subjected to three rainfall simulations which varied in intensity and duration. These results are discussed in Chapters 5 and 6. The experimental procedure is represented diagrammatically in Figure 3.3.1.

During Stage I, short-term hydrological data were collected which included:

1) rainfall duration (hours);
2) total rainfall (g);
3) total discharge (g).

Knowing the rainfall input and discharge output, it was possible to calculate the water retention in the structure from a simple water balance equation (e.g. 3.3.1.):

$$R = Rf - Q \qquad \textbf{Equation 3.3.1}$$

where Rf = rainfall (g);

R = retention (g) and;

Q = discharge (g).

During Stage II, the long-term information on evaporation and changes in retention were calculated. Evaporation (g) was calculated from equation 3.3.2.:

$$E = (OW + R) - W \qquad \textbf{Equation 3.3.2}$$

where E = evaporation (g);

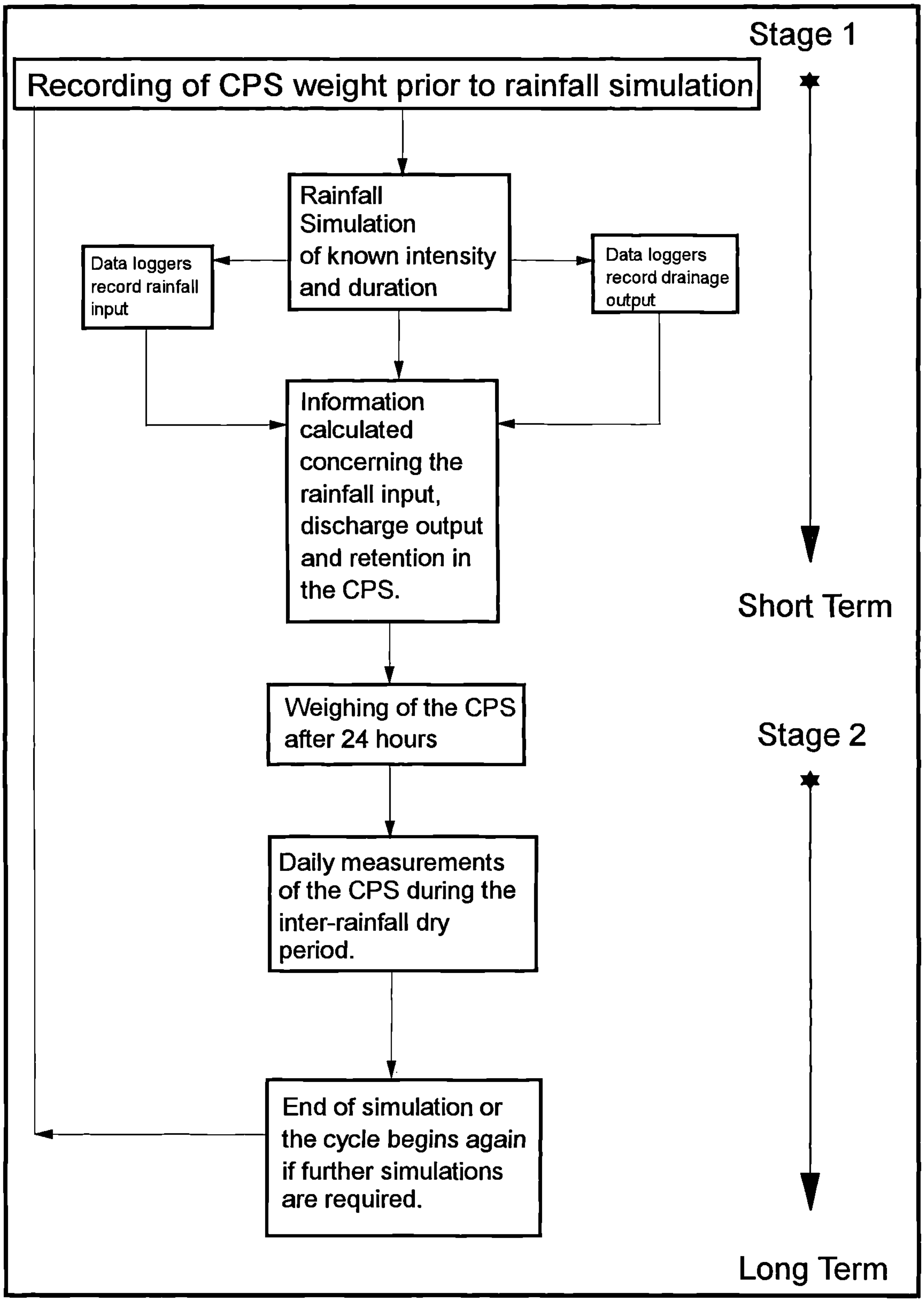
OW = the original weight of the box before rainfall simulation (g);

R = retention (g) and;

W = the weight of the box following the rainfall simulation (g).

Variations in Rainfall Intensity and Duration.

In an attempt to standardise the analysis of results, a constant volume of precipitation was applied to the boxes during each rainfall simulation. A rainfall volume of 5.4 litres was chosen, which was equivalent to a 15 mm rainfall of one-hour duration over the box surface (see Table 3.3.1). The 15 mm event was chosen because it is typical of a two-year return interval storm event in the British Isles, which is frequently used in storm drainage design (Rodda *et al.*, 1976). The size of storm was also within the capabilities of the experimental design, i.e. the volume of water could be contained within the pressurised barrel without having to interrupt the experiment in order to refill the container.



<u>Figure 3.3.1.</u> The Procedure for the hydrological investigation. Stage I finished 2 hours after rainfall ceased. Stage II was completed if a further simulation was intended. CPS is the Car Park Structure.

Table 3.3.1 Data on the rainfall simulations experienced by all boxes.

Rainfall Simulation Test no.	Duration of simulation (hours)	Equivalent Rainfall Depth (mm)	Rainfall Intensity (mm h^{-1})	Return Interval (R.I) in Years
1	1	15	15	2
2	0.5	15	30	5
3	2	15	7.5	1

The sequence of three storm events per box, with various intensities, also allowed data to be obtained on the responses to consecutive storm events with differing inter-rainfall dry periods. The volumes of rainfall retained during a single storm and the changes in retention over time were also calculated. After the three sets of rainfall simulations were completed, a 3-hour storm event with a greater volume of water (10 litres) was applied to the boxes (approximately 9.26 mm h^{-1} equivalent rainfall intensity). The intention here was to establish if these higher volumes of rainfall influenced the overall retention within the structures.

This volume was chosen because it was within the equipment limitations and it was estimated that the rainfall volume and duration were great enough to saturate the structure.

3.3.3 Clogging Simulations on the Boxes

Previous research identified clogging as a disadvantage when using permeable pavement structures (Field *et al.*, 1982; Hogland *et al.*, 1987; Raimbault, 1990; Hogland, 1990). Clogging at the surface would reduce surface infiltration rates and clogging at the base of the structure would reduce percolation rates into the sub-soil.

If clogging occurred at the base, water could still be retained within the structure. It was considered important to identify where clogging occurred within the structure.

Clay particles are known to be important for heavy metal absorption (Kennedy, 1965; Förstner and Wittmann, 1983; Gibson and Farmer, 1984; Meseure and Fish, 1989), and it was considered important to examine the migration of clay through the model permeable pavement car park structure. Organic material is also known to influence heavy metal and contaminant migration (Cline and Upchurch, 1973; Ellis, 1990). The graded sands represented the coarser sediment load.

Experiments were designed to identify whether clogging influenced the hydrological performance of the model car park surface. These experiments applied extreme particulate loadings onto the model boxes, in an attempt to cause failure of the structure and to ascertain the structure's lifespan. Boxes containing surface blocks and pea gravel were used during these clogging experiments (three different grain sizes of pea gravel were examined). The results are discussed in Chapter 7.

To aid the decisions on the amount of sediment load to be applied, information was sought on sediment loading in stormwater runoff from other British research projects. Information gathered in 1985 from Clifton Grove, Nottingham (Pratt and Fletcher, 1987) provided information on the type and grain size of sediment loaded onto car parks in an urban environment. In order to reduce the variables in the clogging experiments, it was decided that two separate experiments would be conducted; the first would apply clay and organic (peat) fractions only, to reduce any confusion between the migration of clay and graded sand fractions; and the second experiment

Table 3.3.2 **Information on the clogging experiments.**

Experiment	Type of addition	Load applied on the car park surface (g)	Load applied on the car park surface (g m^2)	Load applied on the car park surface (Years equivalent)
Experiment 1	Clay (66.7%) Peat (33.3%)	365	1.014	80
Experiment 2	Graded sands	1.873	5.203	140

would apply graded sands. The sediment and rainfall volumes applied are given in detail in Appendix C. Materials selected to clog the model boxes were clay (kaolinite); peat (representing the organic fraction); and graded sands. This allowed a simple analysis of clogging without having the concern of using toxic materials. Table 3.3.2 gives the load and type of particulate additions for the two experiments.

Experiment applying clay and organic fractions.

The experimental design incorporated three grain size mixtures of bedding materials within the model structures as shown in Table 3.3.3. Table 3.3.3 also gives the type of material additions used in the experiments. The equivalent of 20-year loads from the Clifton Grove data were applied during each clogging simulation by applying 50.7 g m^2 of material. After the particulates were evenly applied (see Plate 3.3.1) a 15 mm, one-hour duration, rainfall event was simulated. The extreme loadings are applied in an attempt to cause blockage of the surface. In total, the equivalent of 80 years of particulate load (365 g) was applied to the boxes during the first clogging simulations (clay and peat fractions). Once the load was applied, the boxes were subjected

Plate 3.3.1 The separating device used during particulate applications.

to five more rainfall events to allow the particulates to be transported into the bedding material.

Experiment applying graded sands.

Once the clay and organic fractions were added, the graded sand was applied on 3 of the boxes. The graded sand had a particle size ranging from 75 microns to 1.75 mm (see Table 3.3.4). The load was calculated for each particle size range. An equivalent 20-year loading (743 g m^{-2}) was applied every alternate rainfall event, resulting in a total of 1873 g being applied in the second set of clogging simulation. Table 3.3.4 illustrates the grading of the sand applied.

Table 3.3.3 The material type applied to each box and also the model box components.

Box Number	Contents (all have concrete block surface)	Type of material addition
2	Pea gravel, 5-10 mm Depth 50 mm	Clay
3	Pea gravel, 5-10 mm Depth 50 mm	Clay (66.7%) Peat (33.3%)
4	Pea gravel, 5-10 mm Depth 50 mm	None
5	Pea gravel, 3-5 mm Depth 50 mm	Clay
6	Pea gravel, 3-5 mm Depth 50 mm	Clay (66.7%) Peat (33.3%)
7	Pea gravel, 3-5 mm Depth 50 mm	None
8	Pea gravel, 50% 3-5 mm 50% 5-10 mm Depth 50 mm	Clay
9	Pea gravel, 50% 3-5 mm 50% 5-10 mm Depth 50 mm	Clay (66.7%) Peat (33.3%)
10	Pea gravel, 50% 3-5 mm 50% 5-10 mm Depth 50 mm	None

Table 3.3.4. The load and the percentage of sand (in each grade) applied during the second experiment.

Grain size range	Percentage by weight of sand applied	Actual load of addition (g) the box area
75 microns to 150 microns	9.6	182
150 microns to 1.18 mm	21	398
1.18 mm to 1.75 mm	69.4	1.313
		Total = 1893

After the material loads were applied, the boxes were dismantled to examine the migration of material through the structure. A number of the infiltration inlets were also excavated to examine the degree of clogging. This allowed a comparison to be made between the clogging of the infiltration inlets in the models and at the field sites.

Chapter 7 discusses the results of field measurements of clogging which were undertaken at the Clifton Campus and Gill Street sites, where full-scale structures (with the same surfacing as the model car park structure) have been used as parking facilities since 1986 and 1985, respectively. The field samples were excavated from the infiltration inlets between the surface blocks. Six infiltration inlets were excavated per site with each infiltration inlet comprising two samples (the first being 0-50 mm and the second being 50-100 mm from the surface). The samples were then sieved and the amount of fine sediment was obtained.

The clogging experimental results are discussed in Chapter 7 and the impact of clogging on the hydrological performance of the model car park structure is examined.

3.4 Summary

This chapter has examined the experimental equipment which has been developed during the research project. The equipment is unique and has been examined in some detail in order to present the advantages and limitations of it's use. The use of this equipment and the experimental procedures have also been outlined. The results of the experiments are discussed in Chapters 4 to 7.

Chapter 4 - Hydrological characteristics of concrete blocks and bedding materials.

4.1 Introduction

This chapter discusses the research findings from experiments carried out independently on two main car park components, namely surface concrete blocks and bedding material. Two different types of bedding material were used during experimentation, a pea gravel and a limestone (grain size 5-10 mm). The pea gravel used was of the same lithology but it was sieved into four different ranges of grain sizes, which were 1-10 mm, 5-10 mm, 3-5 mm and 1-3 mm.

This chapter will briefly examine the theory of water movement in a porous medium followed by a general description of the bedding material used before discussing results from a number of experimental sources. Table 4.1 gives a detailed description of the experiments undertaken. This chapter also examines the hydrological performance of model boxes which contained only one component at a time, i.e., a model box containing pea gravel only and a second box containing only surface blocks.

After examination of the research findings, the hydrological performance of the model boxes are predicted using the small-scale experimental results and the accuracy of the predictions is assessed.

Table 4.1. **The experiments undertaken on single box components.**

Experiments	Description of experiment, the scale and the components under study
SET A	Small-scale retention experiments involving a litre volume of bedding material. Various types of bedding materials are examined as are their retention characteristics.
SET B	Small-scale evaporation experiments involving tubes (evaporative surface being 12 cm^2) filled with the bedding material types. Evaporation is monitored over 62 hours.
SET C	Small-scale retention experiments involving 20 concrete surface blocks. The increased retention over time is also examined.
SET D	Small-scale evaporation experiments involving 20 concrete surface blocks. Evaporation volume and rates over 31 days from each block were examined and an average block performance calculated
SET E	Rainfall simulations were carried out on a model car park surface box (600 x 600 mm) containing only pea gravel (grain size 1-10 mm) and **not having** a surface covering of concrete blocks. The retention characteristics were monitored over four rainfall simulations.
SET F	The evaporation in the inter-rainfall dry periods of the above experiments (SET E) were monitored and analyzed in this experiment. Again no concrete surface blocks were present and the surface was totally covered by pea gravel.
SET G	Rainfall simulation on a model box containing only concrete surface blocks. The model box did not contain any pea gravel. Retention by the model box over three rainfall simulations was examined.
SET H	The evaporation during the inter-rainfall dry periods from the above experiments (SET G) were monitored during this experiment.
SET I	Evaporation from the surface of the concrete block was examined by the "wick" experiment. Water was introduced to the block from only the base. Water loss from the top surface was examined.

If predictions can be made of the hydrological performance of the two components using the small-scale results, predictions can also be made of the hydrological performance of model boxes containing both components.

4.2 Background theory on water movement in porous media.

Retention of water within a porous medium.

The bedding material used in the experiments can be compared with a "skeleton soil". The large grain sizes and high permeability of the material will result in infiltration rates being high (over 1000 mm h^{-1}). Infiltration often follows the form of the equation first proposed by Horton (1933), which states:

$$f = f_c + \mu e^{-Kt} \qquad \textbf{Equation 4.1}$$

where:

f is the infiltration rate (mm h^{-1}) at any time;

f_c is infiltration capacity (mm h^{-1});

$$\mu = f_o - f_c;$$

where f_o is initial infiltration capacity (mm h^{-1}) at t=0; t is time (min) from beginning of rainfall; K is a constant (min^{-1}) for a particular soil and surface.

f_o and f_c for a gravel soil will usually yield values of f greater then 220 mm h^{-1} (Wilson, 1992). The infiltration rates for the bedding materials used here were found to be extremely high (over 1000 mm h^{-1}, see Chapter 7).

Water retained by the bedding material after a rainfall simulation is held by surface tension around particles; at surface contact points; and by capillary forces (Todd, 1980; Marshall and Holmes, 1992; Shaw, 1994). The total amount of water retained depends on the specific surface area (total surface area of particles in a given volume of soil), which increases as the grain size decreases and as the particle becomes more flattened in shape rather then spherical (Marshall and Holmes, 1992). For example, sand has a specific surface area of 1 $m^2 g^{-1}$, whereas montmorillonite has a specific surface area of nearly 800 $m^2 g^{-1}$ (Ward, 1975). Therefore, the size and surface area of bedding material, as well as the degree of clogging, will be important in governing water retention.

Movement of water in porous media.

The movement of soil moisture is influenced by a number of factors such as gravity, suction forces (high to low hydraulic potential), vapour pressure and temperature gradients (Smedema and Rycroft, 1988). Particle tension and capillary forces increase as soil moisture decreases. This means that the energy required to lose moisture will be low if there is more moisture and higher if the soil moisture content has decreased (eg. if evaporation or drainage has occurred).

The movement of soil moisture, after infiltration and percolation has ceased, is driven by the hydraulic conductivity and the combined gradients of suction and gravity (Todd, 1980; Marshall and Holmes, 1992; Shaw, 1994). However, water movement is irregular due to varying grain sizes, inter-particle spaces and differing thicknesses of the water film held by surface tension. The process of evaporation creates a suction gradient which results in an upward movement of moisture. Hillel (1971) identified two distinct stages in the drying process of a soil; the first being dependent on soil surface conditions and the second being a declining rate which is influenced by the soil's ability to deliver moisture to the surface. This will result in a slower decrease in the rate of moisture movement (Stage 1) when the soil is wet, followed by a more rapid decline (Stage 2). The second stage, where soil moisture content is reduced, will result in evaporation decreasing due to a decrease in the moisture gradient through the profile.

Wind (1961) suggested that if clay overlies sand the hydraulic conditions created would favour a higher rate of capillary movement through the material to the surface, as compared with sand overlying clays. If it is assumed that the bedding material is the sand and clogging occurs at the surface rather then in the basal areas (by clay), then it could be expected that the presence of the clays on the surface would increase moisture loss (by evaporation), due to a higher rate of upward movement of moisture by capillary forces. Experiments on clogging were designed to see if this characteristic was observed on the model car park structure (see Chapter 3, section 3.3.3).

4.3 Bedding material particle size and shape.

Particle shape analysis was undertaken to aid the explanation of the varying hydrological performances of the bedding material. Various methods can be used to classify gravel shape (Briggs, 1977; Allen, 1985), including Zingg's classification, Krumbeins sphericity index and Cailleux flatness index. Since flatness may have a significant influence on the water retention (Marshall and Holmes, 1992) the Cailleux's index was chosen for comparison. The flatness index is defined by equation 4.2:

$$\text{Flatness} = (A + B)/2C \qquad \textbf{Equation 4.2}$$

where:

A, B and C are the length of the axes of the particle (see glossary list, Appendix B, for definition).

The higher the flatness value, the greater the grain shape resembles a disc. The minimum value of 1 indicates an equi-dimensional particle (a sphere). 200 particles of each gravel type used in the construction of the model boxes were measured and the flatness values were calculated. The pea gravel (1-10 mm) had a flatness value of 2.19 and the limestone 2.25. This indicated that the limestone had a marginally more disc-like grain shape when compared with the pea gravel.

The gravel samples were also measured to produce grading indices. The average axis value was calculated using Equation 4.3:

$$(A + B + C) / 3 \qquad \textbf{Equation 4.3}$$

Where A, B and C are defined in Equation 4.2. Percentage frequency distribution curves were produced from the measurements. Figure 4.1 illustrates the cumulative percentage frequency curves for the pea gravel and limestone samples. The pea gravel percentage frequency curve shows axis values ranging between 3.2 - 6.8 mm whilst the limestone curve had values between 4.3 - 7.7 mm. The greater average axis length of the limestone and it's grain shape suggests that it will be able to retain more water and conversely evaporate more water compared with the pea gravel (1-10 mm). This may have implications when considering the optimum retentive and evaporative surface for a model car park surface.

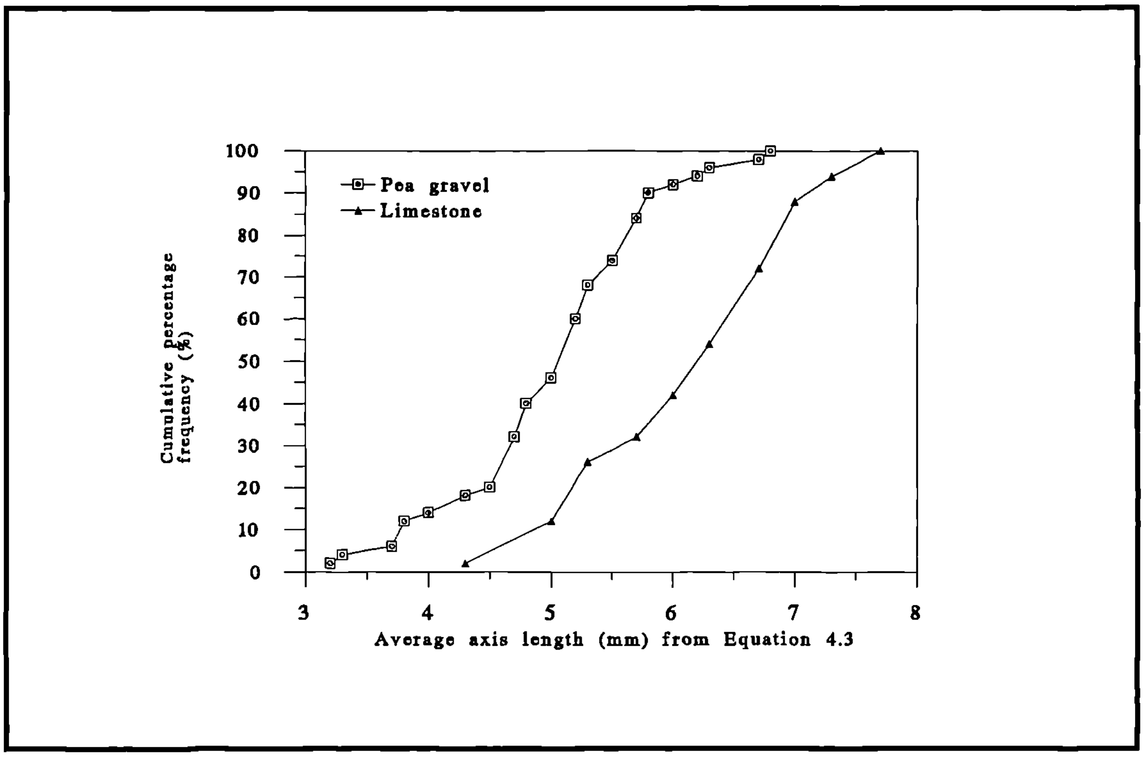


Figure 4.1 **The cumulative percentage frequency curves for the limestone and pea gravel (1-10 mm) samples.**

4.4 Small-scale experiments.

The experiments listed in Table 4.1 are discussed in the next section. Each component and hydrological process are examined separately.

4.4.1 Retention characteristics of the bedding material (Set A, Table 4.1).

Table 4.2 gives some of the physical characteristics of the bedding materials used in the construction of the model car park structures. These data are the average values obtained from 10 repeat measurements using a litre volume of gravel which was immersed in water for one hour.

<u>Table 4.2.</u> Hydrological characteristics of the bedding material (based on ten replicates).

Bedding material (volume analyzed 1000 cm^3)	Water retained following 1 hour of draining	Standard deviation	Specific retention: water retained following drainage as a percentage of voids	Porosity = volume of voids / total volume	Bulk density ie. kg mass/ 1 litre
Units	**(g)**		**(%)**	**(%)**	**(g cm^{-3})**
Pea gravel grain size 1-10 mm	69.20	0.5	16.54	41,85	1.46
Pea gravel grain size 5-10 mm	45.59	0.49	11.47	39.76	1.57
Pea gravel grain size 3-5 mm	101.39	0.61	23.59	42.98	1.44
Pea gravel grain size 1-3 mm	132.77	0.72	31.44	42.23	1.46
Limestone grain size 5-10 mm	56.81	0.52	12.64	44.94	1.42

The pea gravel, with a smaller grain size (1-3 mm), retained the most water following 1 hour of drainage (132.77 g). This might be expected since the specific surface area of the smaller grains is greater than the specific surface area for a larger grain size in the same volume (section 4.2). The limestone (5-10 mm) retained slightly more water than the pea gravel (5-10 mm), but less then the other grain sizes and had a strong crystalline structure, which meant that absorption of water was negligible (0.2 g per litre volume of limestone).

During these experiments it was observed that each type of bedding material had a maximum capacity of water retention which was reached after approximately two minutes of wetting and did not increase with a longer contact time with the water. The average porosity of the bedding materials ranged from 39.76 - 44.94%. The average bulk densities of the material (after packing into a litre volume) ranged from 1.46 - 1.57 (g cm^{-3}).

4.4.2 Evaporation Characteristics of bedding material (Set B, Table 4.1).

Experiments were carried out to measure evaporation rates and amounts from the bedding materials. Samples were immersed in water for one hour and then allowed to drain freely under gravity. The weight was recorded after one hour of free-drainage. Subsequent weights were recorded for the next 10 hours (at 1-hourly intervals) and then 62 hours later. Since the bases and sides of the containers were sealed, with only 12 cm^2 of surface area being in contact with the air, any change in weight of the bedding material was due to evaporation from this limited surface area.

The results were calculated as a cumulative evaporation loss (g cm^{-2}). Table 4.3.A gives the observed evaporative losses from the bedding gravels, assuming that the gravels had covered a surface area equivalent to the gravel in the model car park structures, i.e., 15% of the model car park surface area (or 540 cm^2). Table 4.3.B gives these losses in equivalent depths of rainfall (mm) on a car park surface.

The greatest weight loss after ten hours was shown by the limestone sample (Figure 4.2). This may be due to the larger grain surface area exposed, since the limestone had a marginally higher flatness index. However, after 62 hours the greatest total evaporative loss was exhibited by the pea gravel (1-3 mm). From this it can be assumed that, after the initial stages of drying, evaporation was water supply-limited, since the greatest amount of evaporation was exhibited by the smaller grain sizes which retained more water. After 10 hours the effects of grain shape on evaporation became a less dominant factor.

Table 4.3.C gives the evaporation rate (mm h^{-1}) calculated from the results of Table 4.3.B. These results are plotted in Figure 4.3. It is apparent that during the first three hours the evaporation rates varied significantly. In general, the rate of evaporation began to decrease after four hours. Over the period from 10 to 62 hours, the pea gravel 1-10 mm had the lowest hourly evaporation rate (0.016 mm h-1), whereas the pea gravel 1-3 mm had an evaporative rate which was nearly double (0.030 mm h-1). The limestone had the second lowest evaporation rate.

<u>Table 4.3.A.</u> Evaporation (g) from bedding materials (calculations assume the same surface area as the exposed model car park surface of 540 cm^2).

Period	Cumulative water loss from the bedding material Pea gravel 1-3 mm	Cumulative water loss from the bedding material Pea gravel 3-5 mm	Cumulative water loss from the bedding material Pea gravel 5-10 mm	Cumulative water loss from the bedding material Pea gravel 1-10 mm	Cumulative water loss from the bedding material Limestone 5-10 mm
(hours)	(g)	(g)	(g)	(g)	(g)
0-1	6.32	8.21	12.00	8.21	9.47
1-2	12.63	13.26	17.68	10.74	20.21
2-3	21.47	23.37	25.26	16.42	24.00
3-4	26.53	27.79	28.42	21.47	30.95
4-5	30.95	31.58	30.95	25.90	36.63
5-6	34.11	34.74	32.84	29.68	41.68
6-7	36.63	37.26	34.48	32.84	45.79
7-8	38.53	39.16	35.81	35.68	48.95
8-9	40.11	40.74	37.07	38.21	50.84
9-10	41.62	42.00	39.07	40.11	52.11
10-62	126.25	103.58	88.42	85.26	99.16

Table 4.3.B. Evaporation (mm) from various bedding materials.

Period	Cumulative water loss from the bedding material (equivalent rainfall) Pea gravel 1-3 mm	Cumulative water loss from the bedding material (equivalent rainfall) Pea gravel 3-5 mm	Cumulative water loss from the bedding material (equivalent rainfall) Pea gravel 5-10 mm	Cumulative water loss from the bedding material (equivalent rainfall) Pea gravel 1-10 mm	Cumulative water loss from the bedding material (equivalent rainfall) Limestone 5-10 mm
(hours)	(mm)	(mm)	(mm)	(mm)	(mm)
0-1	0.117	0.152	0.222	0.152	0.175
1-2	0.234	0.246	0.327	0.199	0.374
2-3	0.398	0.433	0.468	0.304	0.444
3-4	0.491	0.515	0.526	0.398	0.573
4-5	0.573	0.585	0.573	0.480	0.678
5-6	0.632	0.643	0.608	0.550	0.772
6-7	0.678	0.690	0.639	0.608	0.848
7-8	0.714	0.725	0.663	0.661	0.907
8-9	0.743	0.754	0.687	0.708	0.942
9-10	0.771	0.778	0.724	0.743	0.965
10-62	2.338	1.918	1.637	1.579	1.836

Table 4.3.C Evaporation rates (mm h^{-1})from the various bedding materials.

Period	Water loss Pea gravel 1-3 mm	Water loss Pea gravel 3-5 mm	Water loss Pea gravel 5-10 mm	Water loss Pea gravel 1-10 mm	Water loss Limestone 5-10 mm
(h)	(mm h^{-1})	(mm h^{-1})	(mm h^{-1})	(mm h^{-1})	(mm h^{-1})
0-1	0.117	0.152	0.222	0.152	0.175
1-2	0.117	0.094	0.105	0.047	0.199
2-3	0.164	0.187	0.140	0.105	0.071
3-4	0.094	0.082	0.059	0.094	0.129
4-5	0.082	0.070	0.047	0.082	0.105
5-6	0.059	0.059	0.035	0.070	0.094
6-7	0.047	0.047	0.030	0.059	0.076
7-8	0.035	0.035	0.025	0.053	0.059
8-9	0.029	0.029	0.023	0.047	0.035
9-10	0.028	0.023	0.037	0.035	0.023
10-62	0.030	0.022	0.018	0.016	0.017

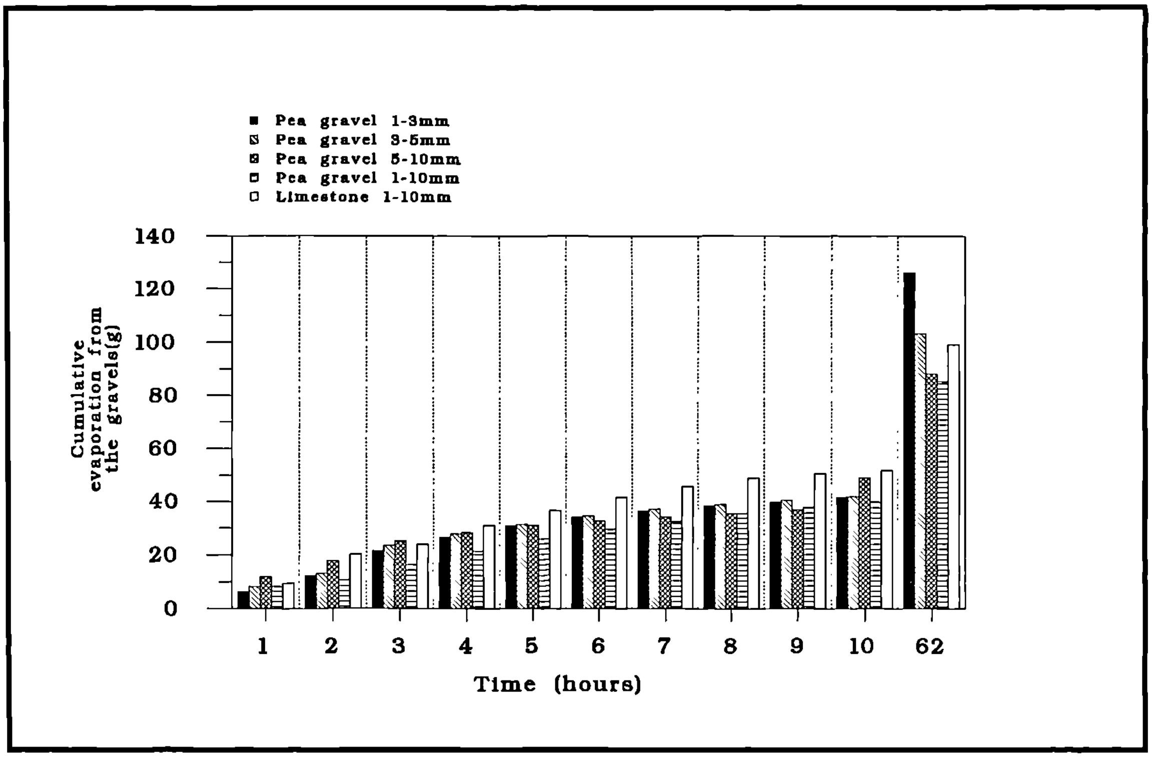


Figure 4.2 Cumulative evaporation from the gravel samples over 62 hours.

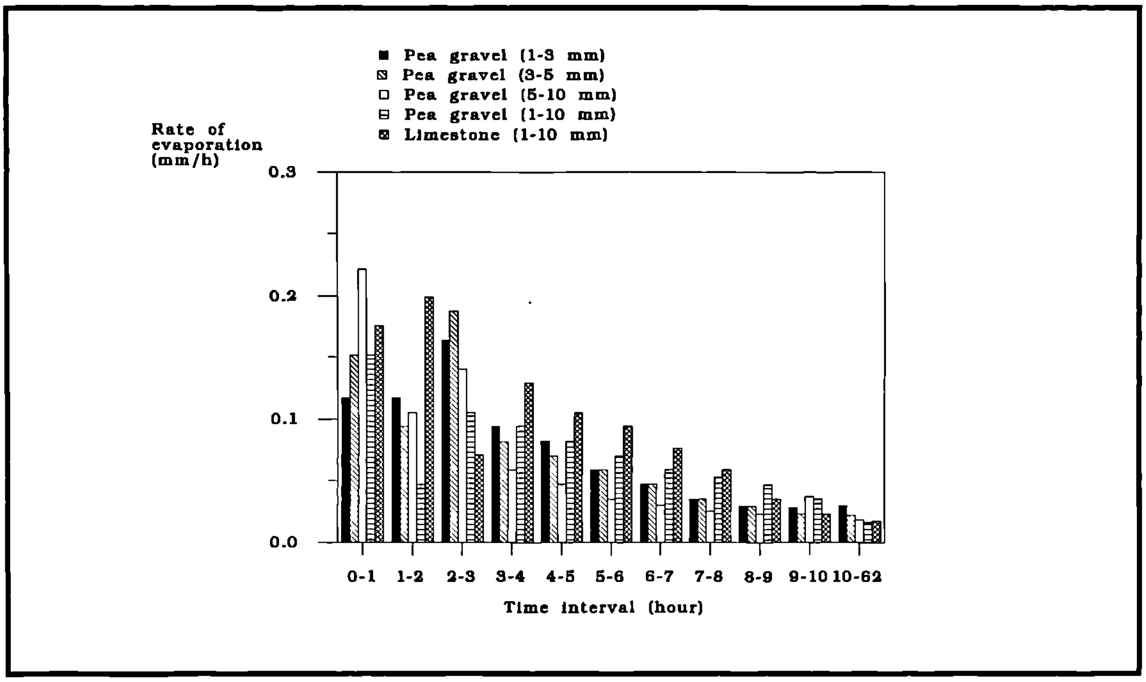


Figure 4.3 Rates of evaporation from the bedding material over 62 hours.

4.4.3 Retention characteristics of the surface blocks (Set C, Table 4.1).

A block absorption experiment (Set C) was carried out on 20 concrete surface blocks. This experiment measured the water absorption by laboratory air-dried blocks during 1 hour of immersion. Table 4.4 illustrates the average water absorption with time. Some 61 g (60% of the total water absorbed in one hour) was absorbed within the first five minutes and over 85% in the first 15 minutes (see Figure 4.4). It was apparent, therefore, that block absorption was rapid during the initial stages of contact with water.

The experiment was continued in order to monitor the water absorption over 24 hours (Table 4.5). Some 83 g (70% of the total water absorption during 24 hours) was absorbed during the first two hours of immersion. This would suggest that the duration of the storm event over the blocks is important in determining the possible retention of rainfall and the overall hydrological performance of the car park structure. Table 4.6.A

Table 4.4. The average absorption of water by the concrete block after experiencing one hour of total immersion in water.

Time period	Time interval	Non-cumulative mass of water absorbed	Cumulative mass of water absorbed	Absorption as a percentage of total mass absorbed in 1 hour
(minutes)	(minutes)	(g)	(g)	(%)
0-5	5	37.35	37.35	61
5-10	5	10.45	47.80	79
10-15	5	4.06	51.88	85
15-20	5	1.55	53.43	88
20-30	10	2.65	56.08	92
30-40	10	2.60	58.68	97
40-50	10	1.18	59.85	98
50-60	10	0.98	60.83	100

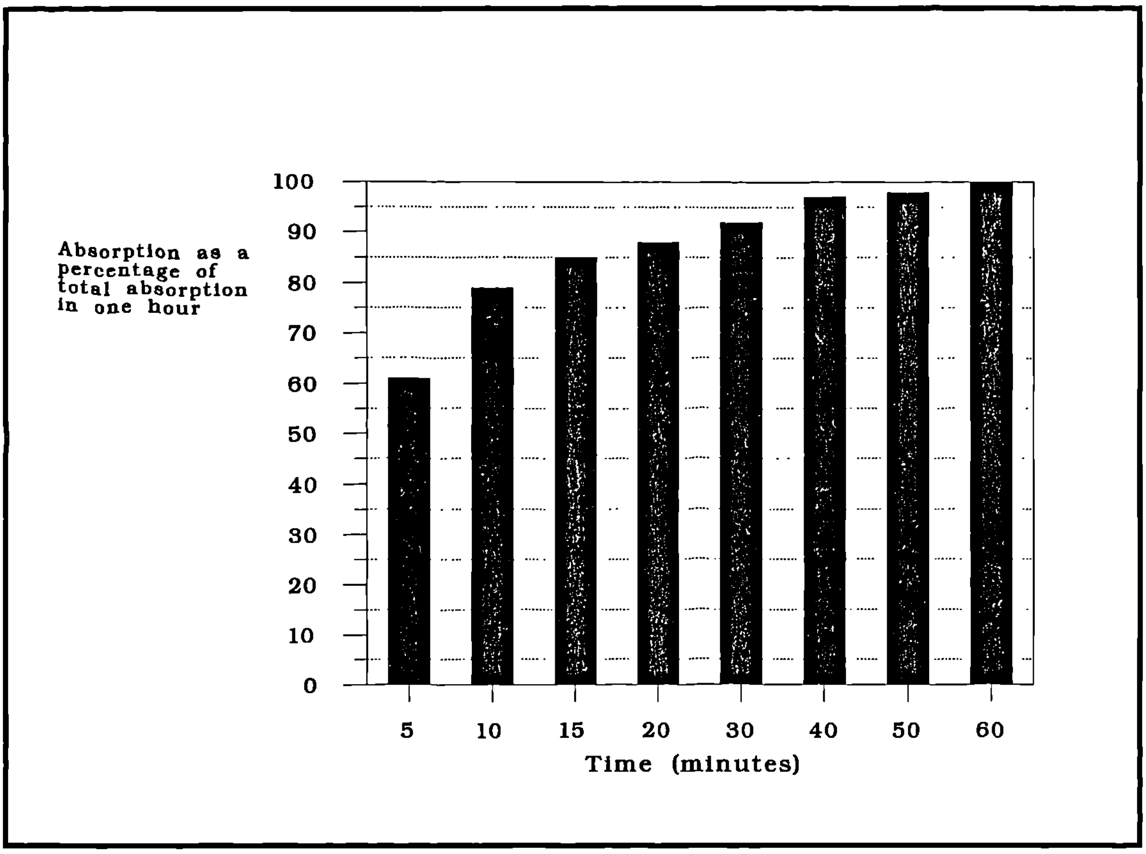


Figure 4.4 **Average absorption of water by surface blocks as a percentage of the total water absorbed in 1 hour.**

Table 4.5. **Average concrete block absorption over 24 hours of immersion in water (* = given previously in Table 4.4).**

Time Period (hours)	Time interval (hours)	Non-cumulative mass of water absorbed	Cumulative mass of water absorbed	Amount absorbed as a percentage of the total absorbed in 24 hours
(hours)	(hours)	(g)	(g)	(%)
0-1	1	60.83 *	60.83 *	51
1-2	1	22.53	83.36	70
2-3	1	4.53	87.90	74
3-4	1	3.58	91.48	77
4-5	1	4.70	96.22	81
5-24	19	22.29	118.51	100

gives the block absorption in grams over a longer time period of 744 hours (31 days). Over this period, some 83 g (49% of the total water absorbed in the 744 hours) was absorbed in the first two hours. After 77 hours (three days), the rate of absorption decreased significantly.

The absorption process was found to be best represented by a semi-logarithmic relationship of the form:

$$A = 68.80 + 37.04\,.\log(t) \qquad R^2 = 0.99 \qquad \textbf{Equation 4.4}$$

where A is absorption (g);
t is time (h).

This is based on results averaged from 20 samples, and is graphically illustrated in Figure 4.5. This relationship is clearly indicative of rapid water absorption during the initial stages of wetting.

Table 4.6.B. gives the cumulative absorption of a concrete surface, in grams and mm equivalent depth of rainfall, per square metre. This table is based on the results from Table 4.6.A. but the absorption has been calculated as absorption per m^2 of the block surface area in contact with water. During the small scale experiments all of the block's surface area was in direct contact with water (894.2 cm^2 total block surface area). The results suggest that after a 1 hour rainfall simulation, 1.9 mm of rainfall can be stored as "retention" in every square metre of concrete surface.

Table 4.6.A. Average surface block absorption of water over 31 days (* = given previously in Tables 4.4 and 4.5).

Time period	Time interval	Non-cumulative absorption Standard Deviation (SD) in next column	SD	Cumulative absorption	Amount absorbed as a percentage of the total absorbed in 744 hours
(h)	(h)	(g)		(g)	(%)
0-1	1	60.83 *	0.81	60.83 *	36
1-2	1	22.53 *	0.79	83.36 *	49
2-24	22	35.15 *	0.79	118.51 *	69
24-77	53	19.69	0.74	138.20	81
77-149	72	10.02	0.73	148.22	86
149-168	19	3.82	0.71	152.04	89
168-269	101	1.50	0.71	153.54	89
269-293	24	4.28	0.71	157.82	92
293-744	451	13.68	0.69	171.52	100

Table 4.6.B. Concrete surface block absorption of water over 31 days.

Time period	Time Interval	Cumulative absorption	Cumulative absorption
(h)	(h)	($g\ m^{-2}$)	($mm\ m^{-2}$)
0-1	1	680.27	1.89
1-2	1	932.23	2.59
2-24	22	1325.32	3.68
24-77	53	1545.52	4.29
77-149	72	1657.57	4.60
149-168	19	1700.29	4.72
168-269	101	1717.07	4.77
269-293	24	1764.93	4.90
293-744	451	1918.14	5.33

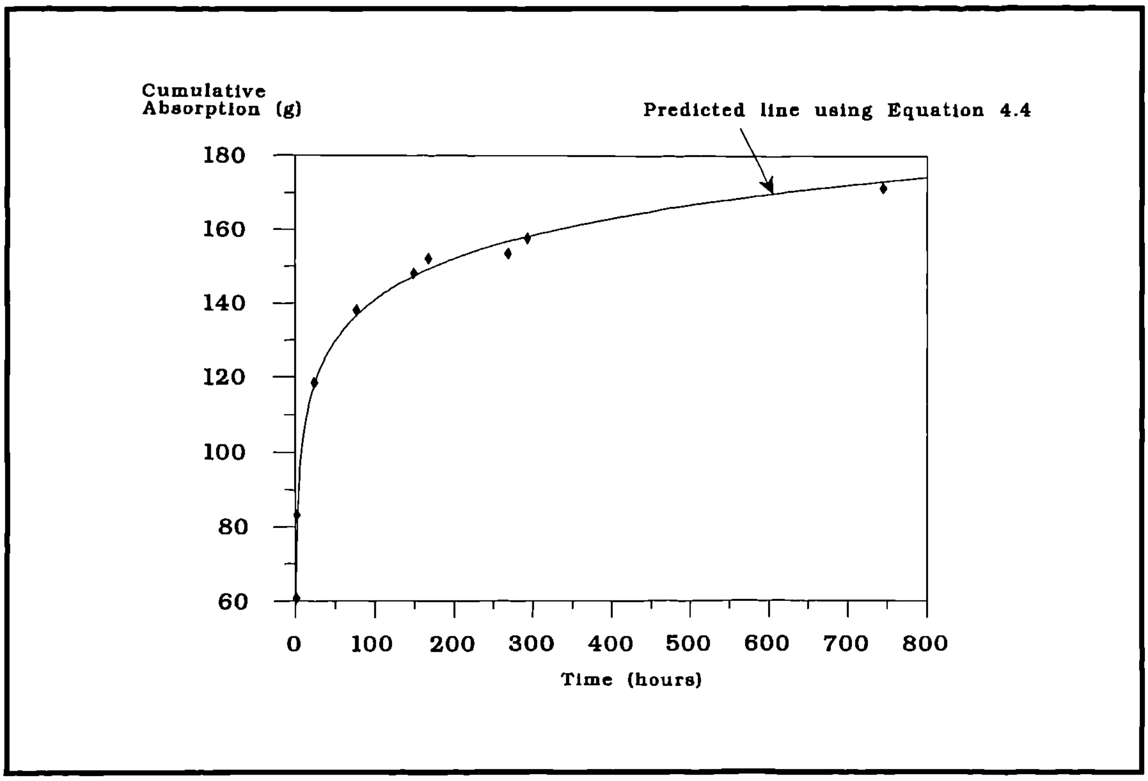


Figure 4.5 **Average cumulative absorption of water (g) by a surface block.**

4.4.4 Evaporation characteristics of the surface blocks (Set D, Table 4.1).

20 blocks were monitored for water loss by evaporation. The blocks had been submerged for one month (absorbing on average 171.5 g of water per block, with a standard deviation of 1.2 g) and were then left to air dry in laboratory conditions (temperature ranging from 16-18 °C). Figure 4.6 gives the "best fit" curve associated with the average cumulative evaporative loss over time (Table 4.7.A gives the data from which Figure 4.6 was drawn). The relationship was best described by a semi-logarithmic equation of the form:

$$E = -41.62 + 36.41 .\log(t) \qquad R^2 = 0.99 \qquad \textbf{Equation 4.5}$$

where E is evaporation (g);

t is time (hours).

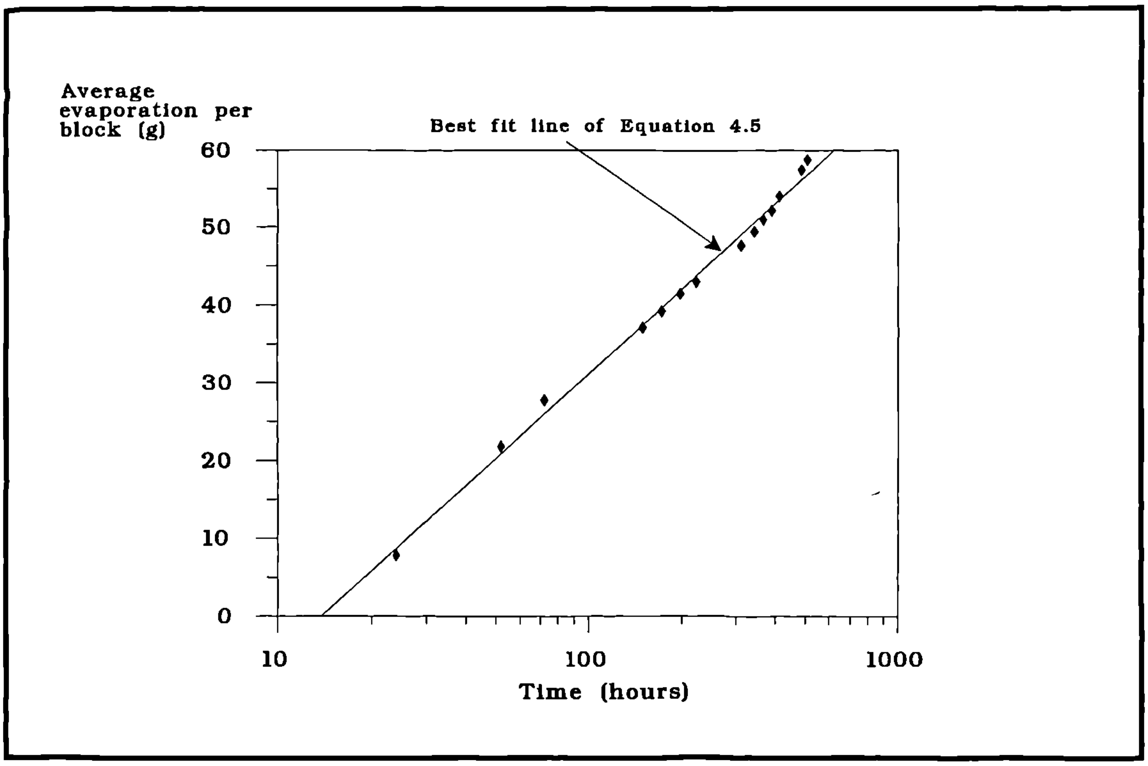


Figure 4.6 **Average cumulative evaporation loss (g) by the surface blocks.**

It is evident from Figure 4.6 that more evaporation occurs during the initial stages of the drying process. One explanation for this phenomenon is that the block may have two areas of water storage, the first area or zone of readily available water being within the first few centimetres of the block surface, and the second zone being located deeper within the block. Alternatively, the water first released is "free" water on the block surface and the second release is chemically-bonded water which takes longer to become free for evaporation. The surface area of the concrete block in direct contact with moving air was calculated to be 724.2 cm^2 per block (the base was not exposed). The evaporative loss (g and mm equivalent depth of rainfall) per m^2 was calculated using the data from Table 4.7.A and is given in Table 4.7.B. The results indicate that after 3 days, over 1 mm of water can be lost by evaporation from 1 m^2 of concrete surface area.

Table 4.7.A. **Measured loss of water by evaporation from a concrete blocksurface .**

Time	Time interval	Average evaporation loss from 20 concrete surface blocks	Standard Deviation	Evaporation loss as a percentage of total water absorbed at each time period (171.5 g/ block)
(hours)	(hours)	(g)		(%)
24	24	7.84	0.1	4.59
52	28	21.83	0.09	12.77
72	20	27.85	0.08	16.29
149	77	37.19	0.07	21.75
171	22	39.32	0.07	22.99
197	26	41.56	0.06	24.30
222	25	43.08	0.06	25.19
311	89	47.72	0.05	27.91
342	31	49.46	0.05	28.92
365	23	51.00	0.05	29.83
389	24	52.20	0.04	30.53
413	24	54.08	0.03	31.63
485	72	57.50	0.03	33.63
509	24	58.84	0.03	34.41

Table 4.7.B. **Loss by evaporation from a concrete block surface.**

Time (h)	Time interval (h)	Loss by evaporation (g m^{-2})	Loss by evaporation (mm m^{-2})	Mean interval evaporation rate (mm m^{-2} h^{-1})
24	24	108.26	0.30	0.013
52	28	301.44	0.84	0.019
72	20	384.56	1.07	0.012
149	77	513.53	1.43	0.005
171	22	542.94	1.51	0.004
197	26	573.87	1.59	0.003
222	25	594.86	1.65	0.002
311	89	658.93	1.83	0.002
342	31	682.96	1.90	0.002
365	23	704.23	1.96	0.003
389	24	720.80	2.00	0.002
413	24	746.76	2.07	0.003
485	72	793.98	2.21	0.002
509	24	812.48	2.26	0.002

Table 4.7.B also shows that there are significant variations in the rates of evaporation over 21 days. The evaporation rate was higher during the first three days of drying, approximately four times greater than after 9 days.

The evaporation rate decreased significantly over the first 7 days from 0.019 mm m^{-2} h^{-1} to 0.004 mm m^{-2} h^{-1}, and then it maintained a constant rate of around 0.002 - 0.003 mm m^{-2} h^{-1} over the next 12 days.

4.4.5 The Wick Effect of the surface blocks.

Chapter 3 (Section 3.2.15) outlined the experimental procedure for examining the loss of water from the block surface. Measurements of weight loss were taken daily over three weeks and the average evaporative loss was found to be 89.87 g day^{-1} m^{-2} or 0.09 mm day^{-1} m^{-2}, when there was a constant (20 mm depth) of water around the base of the block. The top surface of the block was never exposed to water. All loss by evaporation was, therefore, due to water moving through the block. The rate of evaporation was 0.004 mm h^{-1} m^{-2} which compares favourably with the evaporation rates given in Table 4.7.B. There is a good similarity in the rates of evaporation by the surface blocks even though they have been measured using different experimental methods.

4.4.6 Hydrological performance of bedding material and surface blocks - a summary.

1) The retention of water by the bedding materials is influenced by particle size, shape and bedding material lithology. Smaller grain sizes were shown to retain more water after 1 hour submersion and 1 hour drainage. The particles reached their

maximum retention capacity after approximately 2 minutes of submersion, thus suggesting that the particles did not absorb water.

2) During the initial stages of evaporation (10 hours) from the bedding material, particles with a marginally larger shape index (as measured for the limestone in section 4.3) were seen to evaporate approximately 20% more water than the other more spherical particles (pea gravel). However, after 62 hours, the bedding material which retained the most water (pea gravel 1-3 mm, Table 4.2) was seen to have the highest amount of evaporation. The rates of evaporation by all bedding materials vary significantly during the first four hours following 1 hour of drainage. After 4 hours the rates of evaporation generally decreased. The highest rate of evaporation after 62 hours was exhibited by the smaller grain sized bedding material (pea gravel 1-3 mm).

3) Absorption of water by the surface blocks was seen to be rapid during the initial contact time with water, i.e., 60% of the total water absorbed (171.5 g on average) was absorbed in the first five minutes of immersion. The rate of absorption was seen to decrease over contact time with water. However, an upper limit to the maximum absorption was not observed even after one month (744 hours). The absorption process could be represented by the positive semi-logarithmic relationship given in Equation 4.4.

4) Evaporation from the surface blocks can also be described by a semi-logarithmic equation (Equation 4.5). Evaporation experiments showed that 16% of the total water absorbed (on average 171.5 g) was lost during the first 72 hours (3 days) and 23% of the total water absorbed was lost after 171 hours (approximately 1 week), a long term evaporative loss rate of 0.002 - 0.003 mm m^{-2} h^{-1}.

5) The wick experiments showed an hourly evaporation rate of 0.004 mm m^{-2} h^{-1}, if there was a constant supply of water to the base of the block. The block evaporation during this experiment was a result of water moving up through the block to the surface. The rate was slightly higher than the long-term small-scale block experiment, but there was more water available in the wick experiment.

4.5 Hydrological performance of model boxes containing blocks or bedding material.

Two model boxes were assembled, one containing only surface blocks (18 in all) and the other containing only pea gravel. The model boxes contained only one component in order to allow separate analysis of retention and evaporation.

4.5.1 The model box with pea gravel only - Retention characteristics (SET E).

Pea gravel (grain size of 1-10 mm) was placed in a model box to a depth of 50 mm. It was then subjected to four rainfall simulations with varying rainfall intensities (Table 4.8). The volume of rainfall retained varied for each event. The event with the shortest storm duration (Run 2) retained the lowest amount of rainfall (2.67 mm), whereas the event with the longest storm duration (Run 4) retained the most rainfall (3.98 mm). This suggests that the retention in the bedding material increases with an increase in the duration of rainfall. The bedding material appears to be fully wetted only after a long duration rainfall event. The total mass of water held by the bedding material increased over the four events and this may be explained by the increase in storm duration and the pre-storm retention (0, 0.29, 0 and 0.15 mm for Runs 1 to 4 respectively).

Table 4.8. Retention characteristics during four rainfall simulations on a model box containing Pea gravel.

Run	Duration of rainfall	Total rainfall - equivalent depth on the model box surface	Retention of rainfall during each individual event	Total mass of water held by the bedding material	Inter-rainfall dry period.
	(hours)	(mm)	(mm)	(mm)	(hours)
1	1	15.00	2.92	2.92	1.054
2	0.5	15.00	2.67	2.96	307
3	2	15.26	3.65	3.65	401
4	10	50.00	3.98	4.13	383

The methods used to apply water to the box experiments differed from the small-scale experiments. The small-scale experiments experienced saturation and then drainage, whereas the box experiments had water applied to the surface with simultaneous infiltration and drainage, rather than complete saturation. This is likely to explain why the bedding material was only fully wetted after a long duration rainfall event.

4.5.2 Evaporation characteristics (Set F).

Evaporation from the model box containing pea gravel only (with no surface blocks) showed a similar pattern over all four inter-rainfall dry periods. Run 1 is used here as an example. Table 4.9 gives the cumulative evaporation (g); cumulative evaporation in mm equivalent depth of rainfall; evaporation as a percentage of the total water retained within the structure and the evaporation rate between measurement times.

From Table 4.9, it can be seen that 56%, or 1.64 mm equivalent depth, of the total rainfall retained (2.92 mm) was evaporated after 22 hours and over 73% (770 g or 2.14 mm) after 69 hours (nearly 3 days). All of the water retained (1058 g or 2.92 mm) was evaporated

Table 4.9. Evaporation from the model box containing pea gravel only after Run 1. Pea gravel covers 100% of the surface.

Time	Cumulative evaporation	Cumulative evaporation	Evaporation as a percentage of the total retention held within the structure (2.92 mm)	Evaporation rate within the time period
(hour)	(g)	(mm)	(%)	(mm h^{-1})
0-22 TI=22	590	1.64	56	0.075
22-45 TI=23	680	1.89	64	0.012
45-69 TI=24	770	2.14	73	0.010
69-120 TI=51	925	2.57	87	0.008
120-142 TI=22	958	2.66	91	0.004
142-168 TI=26	1.008	2.80	95	0.005
168-190 TI=22	1.022	2.84	97	0.002
190-216 TI=26	1.033	2.87	98	0.001
216-243 TI=27	1.058	2.92	100	0.003

* **TI** is the time interval in hours between each measurement.

after 243 hours (10 days). The evaporation rate was extremely high during the first 22 hours (0.075 mm h^{-1}) but this decreased significantly over the rest of the dry period.

4.5.3 The model box with concrete blocks only - Retention characteristics (Set G, Table 4.1).

A model box was also constructed with blocks only and was subjected to three rainfall simulations with varying rainfall intensities, but with the same volume of rainfall

Table 4.10. **Retention characteristics of the model box containing blocks only.**

Run	Duration of rainfall event	Total rainfall - equivalent depth on the car park surface	Retention of rainfall during individual rainfall events	Total cumulative retention held within the model box (18 blocks)	Inter-rainfall dry period
	(hours)	(mm)	(mm)	(mm)	(hours)
1	0.5	15.00	3.42	3.42	23
2	1	15.00	2.57	5.21	24
3	2	15.26	2.02	6.52	1.531

(Table 4.10). The rainfall simulations were carried out on consecutive days, unlike the pea gravel-only experiments. Table 4.10 shows the retention of rainfall after each rainfall simulation. As the number of rainfall events increased, the retention for each individual event decreased even though the storm duration and water contact time increased. The total amount of water held within the blocks increased over the three rainfall simulations. After the third rainfall simulation, the total retention was almost double that of the water retained after Run 1. To calculate pre-storm retention, the retention after individual rainfall events must be subtracted from the total cumulative retention to give pre-storm retention values of 0 mm for Run 1, 2.64 mm for Run 2 and 4.50 mm for Run 3. Pre-storm retention of water explains why the retention for an individual simulation decreases over the simulations.

4.5.4 Evaporation characteristics (Set H, Table 4.1).

The inter-rainfall dry periods following the first two runs were too short to allow for a detailed examination of the evaporation process and only Run 3 will be examined with regard to evaporation.

Table 4.11.A and 4.11.B give the actual evaporation amounts and rates for the model box containing only concrete blocks, following the third rainfall simulation. The evaporation per m^2 was also calculated. The calculation assumed that each concrete block had an area of 654.2 cm^2 exposed to moving air (i.e., no movement of air past the block sides, but open in the infiltration inlets, at the base and on the top surface). This gave a total concrete surface area of 1.12 m^2 from which evaporation could occur.

On examination of Table 4.11.B, it was seen that after 24 hours 13%(296 g) of the total water retained by the surface blocks had evaporated. The hourly evaporation rate decreased significantly after 24 hours to a quarter of the original rate. The evaporation rates fluctuated during the dry period which may be explained by variations in the laboratory environmental conditions (these are explained more fully in Chapter 6). However, the hourly rate after 122 hours was of a similar magnitude to the wick experiment results in section 4.4.5 which illustrates an hourly rate of 0.003 to 0.004 mm h^{-1}.

<u>Table 4.11.A.</u> Evaporation characteristics of the model box containing only surface blocks.

Time interval (hours)	Actual cumulative evaporation (g)	Actual cumulative evaporation ($g\ m^{-2}$)	Actual cumulative evaporation ($mm\ m^{-2}$)
1-24	296	251.37	0.70
24-101	536	455.18	1.26
101-122	606	514.62	1.43
122-171	676	574.07	1.59
171-197	716	608.04	1.69
197-218	766	650.50	1.81

Table 4.11.B. Evaporation rate and percentage loss from a concrete surface (* from Table 4.10).

Time interval	Period	Evaporation rate for time intervals	Evaporation as a percentage of total retention held (* 6.52 mm)
(hours)	(hours)	(mm m^{-2} h^{-1})	(%)
0-24	24	0.029	13
24-101	77	0.007	23
101-122	21	0.008	26
122-171	49	0.003	29
171-197	26	0.004	30
197-218	21	0.006	32

These evaporation experiments on the model boxes differed with the block experiments outlined in section 4.4.4, in that less of the surface area of blocks in the model box was in direct contact with the atmosphere (654.2 cm^2 per block for a model car park surface; and 724.2 cm^2 per block for the small scale experiments, since only the base was not in direct contact with air). The difference in experimental method may result in predictions based on the individual component analysis giving over-estimations of actual evaporation when compared with the box experiments unless consideration is given to the exposed block surface area.

4.5.5 Hydrological performance of the model boxes - a summary.

1) Retention experiments on the model box containing only bedding material (pea gravel 1-10 mm) suggest that the bedding material is only fully wetted following a long duration rainfall event.

2) Evaporation from the model box containing bedding material had a high evaporation rate immediately following rainfall. The rate decreased significantly over the rest of the inter-rainfall dry period. Comparison of evaporation rates after 69 hours for the model box (section 4.5.4) and the single component analysis (section 4.4.2, Table 4.3.C) showed that the evaporation rate for the model box was lower than the evaporation rate from the single components ($0.010\ mm\ h^{-1}\ m^{-2}$ compared with $0.016\ mm\ h^{-1}\ m^{-2}$ for the single component analysis).

3) Retention by the model box containing surface blocks only showed a decrease in the retention of rainfall during individual rainfall events. However, the total cumulative retention of water increased over successive rainfall events due to pre-storm retention of water.

4) Evaporation from the model box containing surface blocks was of a high rate immediately following rainfall ($0.034\ mm\ m^2\ h^{-1}$). The rate decreased significantly over the inter-rainfall dry period to $0.003\ mm\ h^{-1}\ m^{-2}$.

4.6 Prediction of model box hydrological performance using the results from the individual component analysis.

The results discussed previously have given information on:

1) Small-scale retention and evaporation characteristics of individual bedding material types and sizes (Sets A and B, Table 4.1);

2) Small-scale retention and evaporation characteristics of the surface blocks (Sets C and D, Table 4.1);

3) Model box retention and evaporation characteristics of a box containing only pea gravel 1-10 mm grain size (Sets E and F, Table 4.1).

4) Model box retention and evaporation characteristics of a box containing only surface blocks (Sets G and H, Table 4.1).

In theory, it should be possible to predict the hydrological performance of the model boxes containing the model car park structure (one component only, i.e., blocks or bedding material) using the results from the individual component analysis. The next section compares predictions of hydrological performance using the small-scale individual component results with the actual hydrological performance of the model boxes containing only one box component.

4.6.1 Predictions of bedding material hydrological performance.

Retention predictions.

The model box containing pea gravel had a grain size of 1-10 mm (Sets E and F,Table 4.1). The single component analysis of the retention characteristics of the pea gravel (1-10 mm), gave a retention value of 69.2 g per litre after drainage (Table 4.2). Using this retention value (from Set A experiments in Table 4.1), the retention by a model box containing pea gravel 1-10 mm can be estimated assuming that;

1) Volume of gravel in a model box = 60 x 60 x 5 cm^3 i.e., 18 litres.

2) If 1 litre of gravel retained 69.2 g after drainage, 18 litres would retain 18 x 69.2 g = 1245.6 g of water using these assumptions the volume of water retained by the bedding material can be expressed as:

$R_G = Gv \times Rc$ **Equation 4.6**

where R_G = the water retained by the bedding material;

Gv = the volume of gravel (litres);

Rc = the maximum retention previously calculated (based on the results from Table 4.2).

The model box results (section 4.5.1, Table 4.8) showed that the total retention of water over the four rainfall simulations was 2.92 mm, 2.96 mm, 3.65 mm and 4.13 mm for Runs 1, 2, 3 and 4 respectively.

If the predicted result (based on small scale experiments) of 1245.6 g (3.46 mm equivalent depth of rainfall) is compared with the actual average value of the model box of 1229.4 g (3.42 mm equivalent depth of rainfall), the prediction over-estimates the actual box retention by 1%. The difference is negligible and, from this analysis, it is concluded that Equation 4.6 can be used to estimate the retention of water by the bedding materials in the model boxes using the retention values of Table 4.2.

4.6.2 Evaporation predictions.

A comparison of evaporation between the small-scale single component results (section 4.4.2, Set B) and the model box containing pea gravel-only can not fully be undertaken since the small-scale experiments had a duration of only 62 hours. However, it is possible to compare the evaporation after 69 hours from the model box with a predicted value based on the results of the small-scale experiments.

The model box had an evaporative loss of 2.14 mm (Table 4.9) after 69 hours following rainfall. The small-scale (Set B) analysis showed that the pea gravel (1-10 mm grain size) lost 1.58 mm after 62 hours by evaporation (Table 4.3.B). The time difference in the duration of monitoring was 7 hours (i.e., 69 hours for the model box experiment and 62 hours for the small-scaled experiments). The evaporation rate of the small-scale experiments up to 62 hours had been 0.016 mm h^{-1} (Table 4.3.C). Therefore an estimate of the evaporation from a small-scale sample after 69 hours can be obtained from:

1.58 + (0.016 x 7) = 1.69

If the actual model box evaporation amount (2.14 mm) is compared with the predicted evaporation rate based on the small-scale experiments (1.69 mm), the prediction under-estimates the actual model box evaporation by 21%. The difference may be due to scale effects when calculating evaporation since the small-scale experiments have a much smaller surface area (12 cm^2 for bedding material experiments) which is multiplied up to provide a comparison with the model car park surface having a surface area of 3600 cm^2.

4.6.3 Predictions of block hydrological performance -Retention predictions.

The block retention and absorption processes were best described by a semi-logarithmic relationship for the small-scale experiments (Equation 4.4). The model box experiments containing blocks only gave the total retention of water as 3.42 mm for Run 1, 5.21 mm for Run 2 and 6.52 mm for Run 3. If block retention is calculated using Equation 4.4, using the storm durations of Table 4.10, an estimate of model box retention can be obtained (it must be remembered that Equation 4.4 is based on absorption (g) from a single block). Table 4.12 gives the results.

The percentage difference (percentage under-estimation of actual retention) increases with the number of rainfall events. This is not surprising as Equation 4.4 is based on absorption by surface blocks with no pre-storm retention. It was observed in section 4.5.3 that the

Table 4.12. **Prediction of retention using Equation 4.4 for a model box containing 18 surface blocks.**

Storm duration	Retention predicted using equation 4.4	Actual model box retention	Percentage under-estimation of the actual box retention
(hours)	(mm)	(mm)	(%)
0.5	2.86	3.42	16
1	3.41	5.21	34
2	3.97	6.52	39

water contact time of blocks was important in determining the total amount of water retained. Therefore, predictions of block retention were made using the cumulative contact time with water (Table 4.13). Again the percentage difference increases with the number of storm events, even when water contact time was taken into account. In section 4.5.3 it was observed that the pre-storm retention increased over successive rainfall events. If the predictions using Equation 4.4 (Table 4.12) are used in addition to the pre-storm retention data given in section 4.5.3, the predictions produced are those in Table 4.14.

The estimates for Runs 2 and 3 over-estimated the observed box retention. However, calculations using Equation 4.4 and considering pre-storm retention (as given in Table 4.14) produces a lower percentage difference then the two previous methods of calculating block retention. The accuracy of the prediction is still poor (i.e., 30% over-estimation after Run 3) and this difference will be discussed in more detail in Chapter 5.

Table 4.13. **Prediction of water retention using Equation 4.4.**

Total contact time with water	Predicted water absorption	Actual retention	Percentage under-estimation of actual box retention
(hours)	(mm)	(mm)	(%)
0.5	2.86	3.42	16
1.5	3.74	5.21	28
3.5	4.41	6.52	32

Table 4.14. **Prediction of model box retention including pre-storm retention.**

Run	Pre-storm retention	Prediction using equation 4.4	Sum of previous 2 columns	Percentage difference from the actual model box retention values (5)
	(mm)	(mm)	(mm)	(%)
1	0	2.86	2.86	16% under-estimation
2	2.70	3.41	6.16	16% over-estimation
3	4.51	3.97	8.48	30% over-estimation

4.6.4 Evaporation predictions.

Evaporation rates from the small-scale block experiments were best described by a semi-logarithmic equation (Equation 4.5). Since the inter-rainfall dry period for the model box experiment was only 218 hours, a comparison between the model box and small-scale experiments (up to 222 hours, Table 4.7.A) was undertaken.

Figure 4.7 illustrates the cumulative evaporation (mm) from both the model box and small-scale experiments. A "best fit" curve was applied in order to allow for a comparison of evaporation rates to be made. Since Y=a+b log(x), (see Appendix B, glossary, for definitions) any variations in the value of b would indicate varying evaporation rates over the dry period. The b value for the model box evaporation curve was 472.63 and for the small-scale experiments was 642.72 (36% greater than the model box). This indicates that the evaporation rate from the model box was lower than the small-scale box experiment. This is not surprising since, in section 4.5.4, it was noted that the blocks in the model box had less of their surface area in direct contact with the atmosphere, therefore, reducing the opportunity for evaporation to occur. As a result, the predictions based on the small-scale experimental results may over predict evaporation from a model box by approximately 36%.

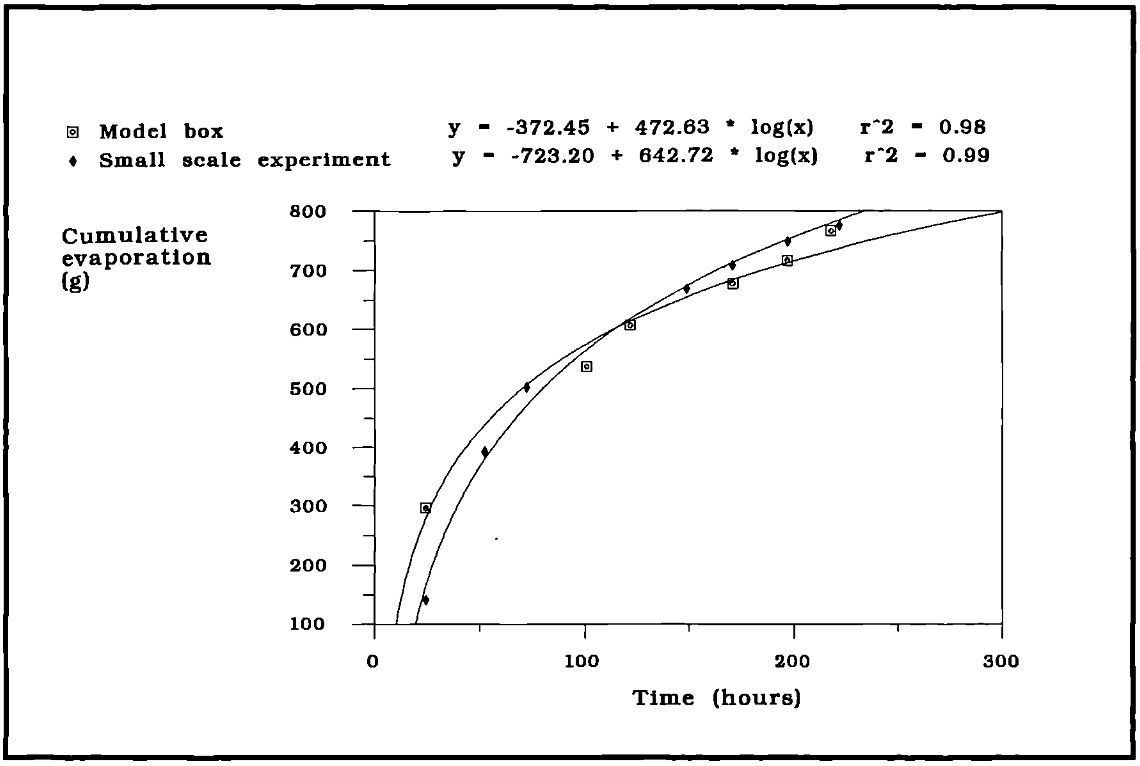


Figure 4.7. **Cumulative evaporation from the model box and the predicted evaporation using small scale experiments.**

4.6.5 Hydrological performance predictions - Conclusions.

1) Predictions of retention by a model box containing pea gravel only using small-scale experimental results proved to be very accurate (99%) using the retention data of Table 4.2.

2) Predictions of evaporation by a model box with pea gravel using small-scale results under-estimate the actual box evaporation by 21%.

3) Predictions of retention by a model box containing surface blocks and using Equation 4.4 proved to under-estimate block retention. The percentage difference increased over consecutive storms. If pre-storm retention values were added to the predictions using Equation 4.4, the percentage difference was less and the accuracy of the prediction improved.

4) Predictions of evaporation by a model box containing blocks, using small-scale experimental results, tend to over-estimate the actual evaporation rate if Equation 4.5 is used since Figure 4.7 shows that the rate of evaporation was lower from the model boxes compared with the small-scale experiments.

Chapter 5 -Short-Term Hydrological Experiments.

5.1 Introduction

This chapter examines the hydrological performance of the model car park structures from the onset of rainfall up to two hours after rainfall ceases. Since the retention by, and discharge from, the model structure governs the effectiveness of the structure to act as a rainfall attenuation device, factors influencing these processes were considered in some detail. The main factors influencing retention and discharge were rainfall intensity, the structural components and the pre-storm retention in the model structures.

The following values were calculated from the raw data collected from the hydrological experiments:

a) rainfall over time (mm),

b) rainfall intensity (mm h^{-1}),

c) discharge over time expressed as a rainfall equivalent (mm),

d) water retention over time expressed as a rainfall equivalent (mm).

From these calculations, an analysis of discharge and retention in relation to rainfall intensity, pre-storm retention and the two structural components, could be performed. Table 5.1 lists the variables and calculations used to produce the final information on short-term hydrological processes. Three different rainfall intensities were employed in the experimental procedure (15, 30 and 7.5 mm h^{-1}). Section 3.2.13 identified the difficulties in maintaining a constant rainfall intensity during the experimental simulations. Reference to rainfall intensities in the following section are the target intensities ie:

15 mm h^{-1}, is the application of 5.4 litres of water during a rainfall simulation with a duration of 1 hour; 30 mm h^{-1}, is the application of 5.4 litre of water during a rainfall simulation with a duration of 0.5 hours; 7.5 mm h^{-1}, is the application of 5.4 litres of water during a rainfall simulation with a duration of 2 hours.

The experimental design did not allow for the model boxes to become laboratory dry after a rainfall event. Therefore, the pre-storm retention within the structures will also be considered since this will influence retention and discharge of rainfall during the subsequent rainfall events. A definition list of the terms used in this section is given in the glossary, Appendix B.

Table 5.1. The variables and associated calculations used during data analysis.

Variable	Calculation	Units
Time (hours)	Raw data taken from data loggers	(h)
Rainfall, Weighing Balance (A) data	Raw data taken from data loggers	(g)
Rainfall mass	Rainfall weight	(g)
Cumulative rainfall	rainfall mass converted into mm = rainfall / area (360)	(mm)
Rainfall intensity	= ((rainfall (g) *t2* - rainfall (g) *t1*) X ((time (min) *t2* /60) - (time (min) *t1* /60)))) / 360	(mm h^{-1})
Discharge, Weigh Balance (B) data	Raw data taken from data loggers	(g)
Cumulative discharge	Discharge data converted into mm = Discharge (g) / Area (360)	(mm)
Discharge, non-cumulative	Discharge data non-cumulative = Discharge (mm) *t2* - Discharge (mm) *t1*	(mm)
Cumulative storm retention	= (rainfall mass (g) - discharge weight (g)) / 360	(mm)

5.2. Hyetograms and hydrographs.

Hyetograms and hydrographs for each model box during all rainfall simulations were drawn in order to examine the response of drainage to rainfall intensity. It was necessary to examine the drainage response because it provided an insight into the structure's ability to attenuate water movement under varying rainfall intensities. Two questions were addressed at this point:

1. Is the discharge response influenced by rainfall intensity ?
2. Do the structural components influence discharge response ?.

The data loggers recorded information at 30 second intervals for up to 2 hours after rainfall ceased; the first reading being taken at the onset of rainfall. These data were then re-computed as 30-second intensities (in mm h^{-1}), as in Figure 5.1. Initial inspection of the hyetograms and hydrographs suggested that the time interval of 30 seconds produced a data set with considerable "noise". This was especially true of the hyetogram (Figure 5.1) which exhibited periodic low readings of rainfall intensity. These fluctuations were also reflected in the hydrographs (Figure 5.1), showing that the short-term discharge patterns were closely associated with fluctuations in rainfall intensity. These fluctuations were seen to occur with a periodicity of every 4-6 minutes. It was observed subsequently that these time intervals were approximately the same as the time interval at which the air compressor cut in to increase the pressure in the rainfall simulator and is, therefore, an artefact of the experimental procedure.

An attempt was subsequently made to filter out these fluctuations in order to identify general trends in rainfall intensity and drainage response. The data were re-calculated using the average rainfall intensities and discharge values over three different time intervals, namely, 3, 6 and 9 minutes. The intervals were chosen because they were divisible by 60, making calculations less complicated. Figures 5.2, 5.3 and 5.4 illustrate the hyetograms and hydrographs produced at these time intervals. The Box 5 experiment is selected as an example to illustrate the impact on this filtering process. The 30-second time interval hyetogram and hydrograph show considerable noise associated with the changes in air pressure feeding the rainfall simulator. For a 3-minute integration (Figure 5.2), the effect of the compressor could also be identified, although the averaging over 3 minutes had smoothed the data to some extent.

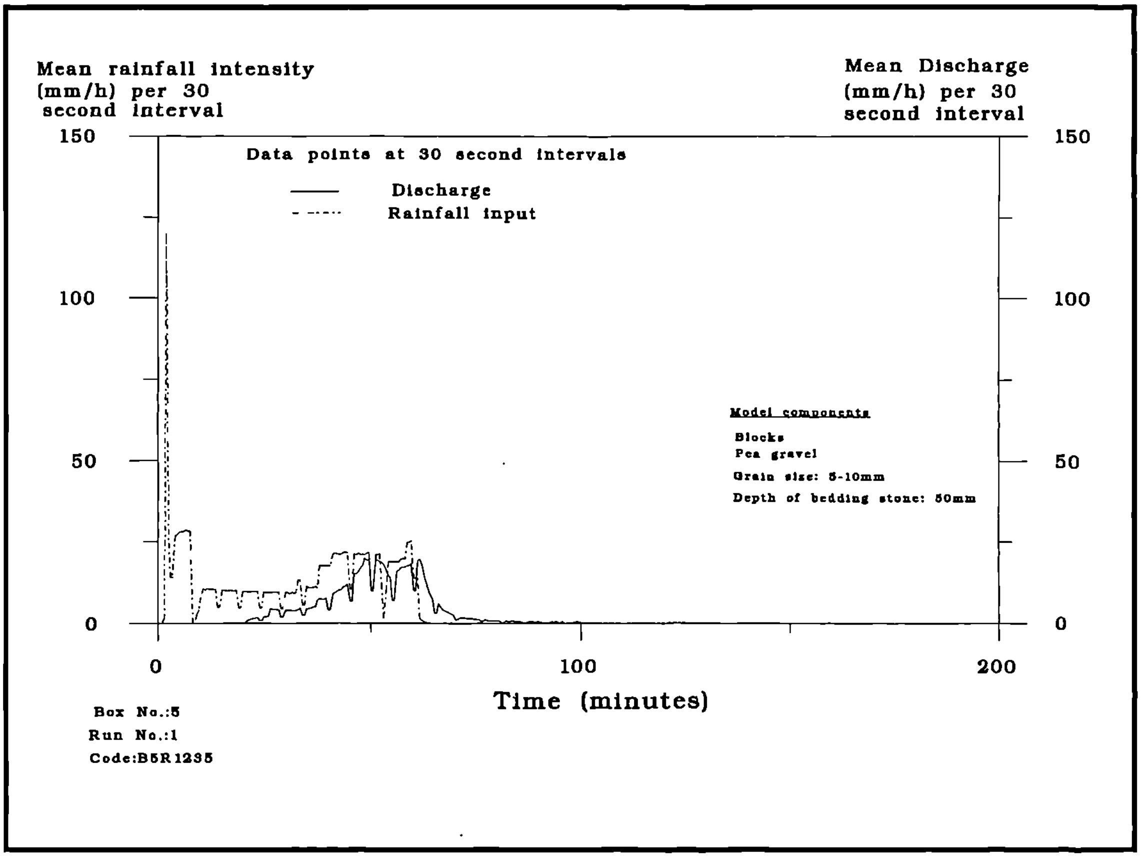


Figure 5.1 Hydrograph and hyetogram for Box 5 using a 30 second integration.

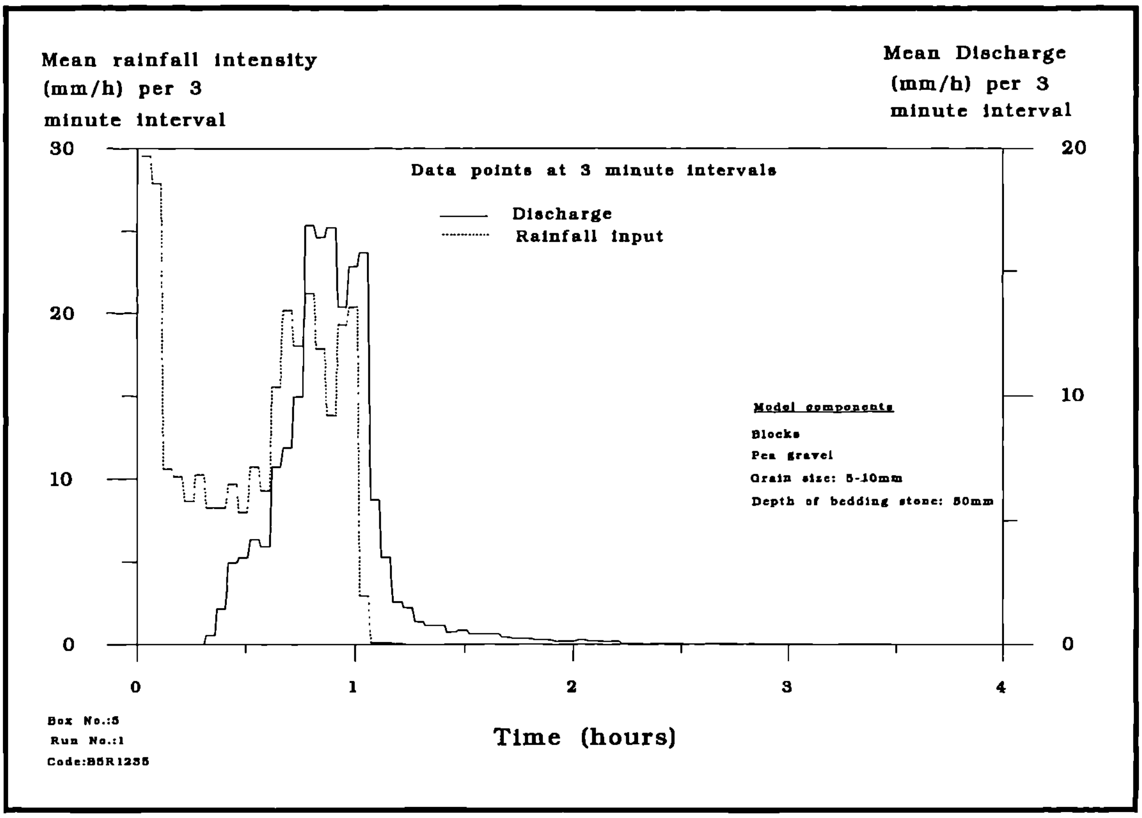


Figure 5.2 Hydrograph and hyetogram for Box 5 using a 3 minute integration.

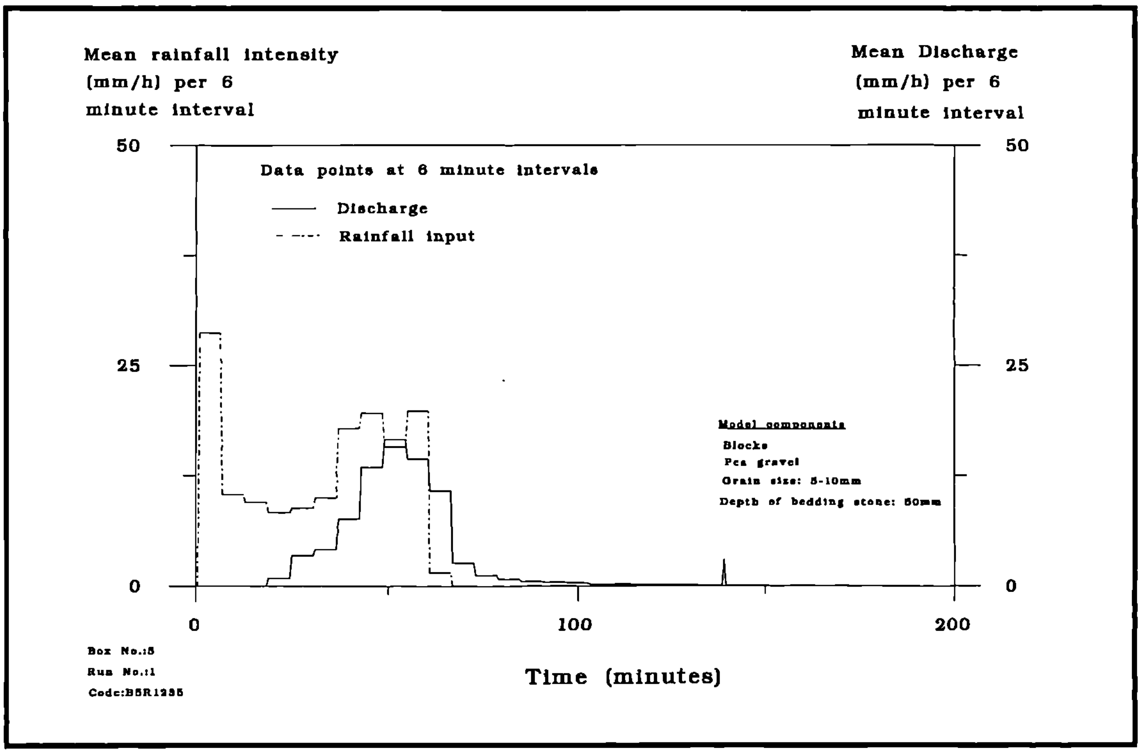


Figure 5.3 Hydrograph and hyetogram for Box 5 using a 6 minute integration.

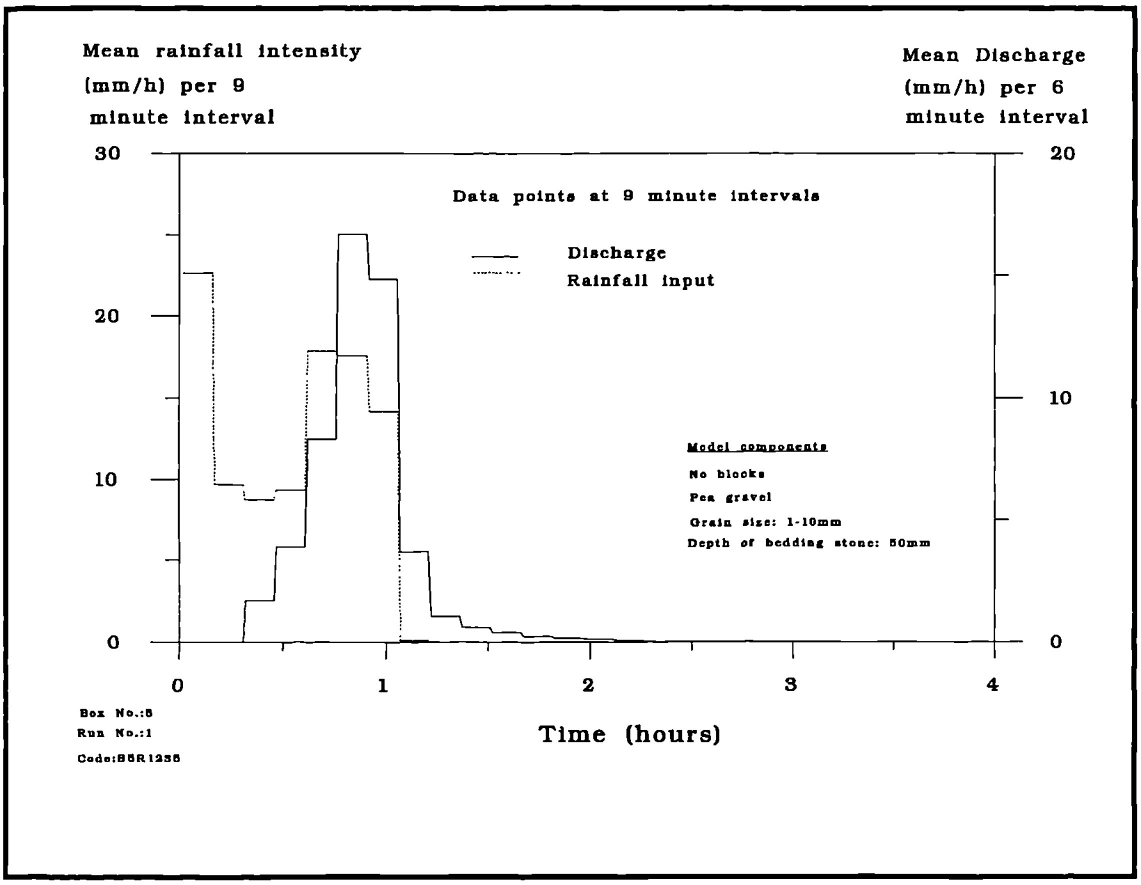


Figure 5.4 Hydrograph and hyetogram for Box 5 using a 9 minute integration.

The 6-minute integration (Figure 5.3) smooths the data further and was effective at reducing the effect of the compressor, allowing the general patterns in rainfall intensity and discharge to be examined. The 9-minute integration (Figure 5.4) illustrated how excessive smoothing disguises the general trend. On examination of the hydrographs and hyetograms at different time intervals for all experimental simulations, the 6-minute interval was regarded as being the most effective at reducing noise, but at the same time providing sufficient data on general patterns to be informative. As a result, the 6-minute integration was chosen as the most suitable for further detailed analysis.

5.2.1. The impact of rainfall intensity

As discussed in section 5.1, three varying rainfall intensities were applied to each model box. Box 8 is used here to exemplify the response. Figures 5.5 to 5.7 show the hyetograms and hydrographs for the three consecutive rainfall simulations with the rainfall intensity being 15, 30 and 7.5 mm h^{-1} respectively. Figure 5.5 illustrates the general trends for the model boxes during the 15 mm h^{-1} rainfall simulation. There was an initial lag in response of the hydrograph to the hyetogram until the rainfall had infiltrated through the structure. This is referred to as the wetting phase. Once the wetting phase was complete (approximately 30 minutes in this instance) the hydrograph began to mirror the hyetogram, especially when there were any great variations in the rainfall intensity, ie. at points A, B and C.

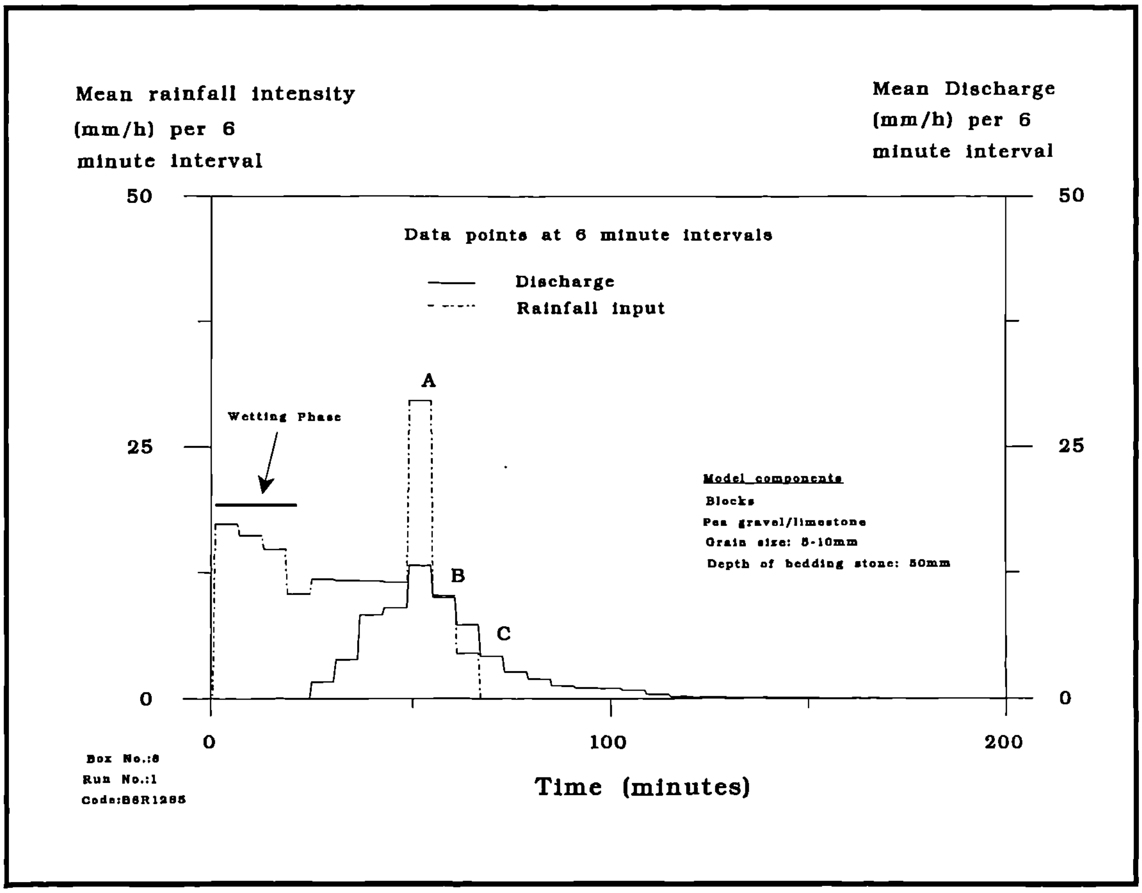


Figure 5.5 Hydrograph and hyetogram for Box 8 Run 1.

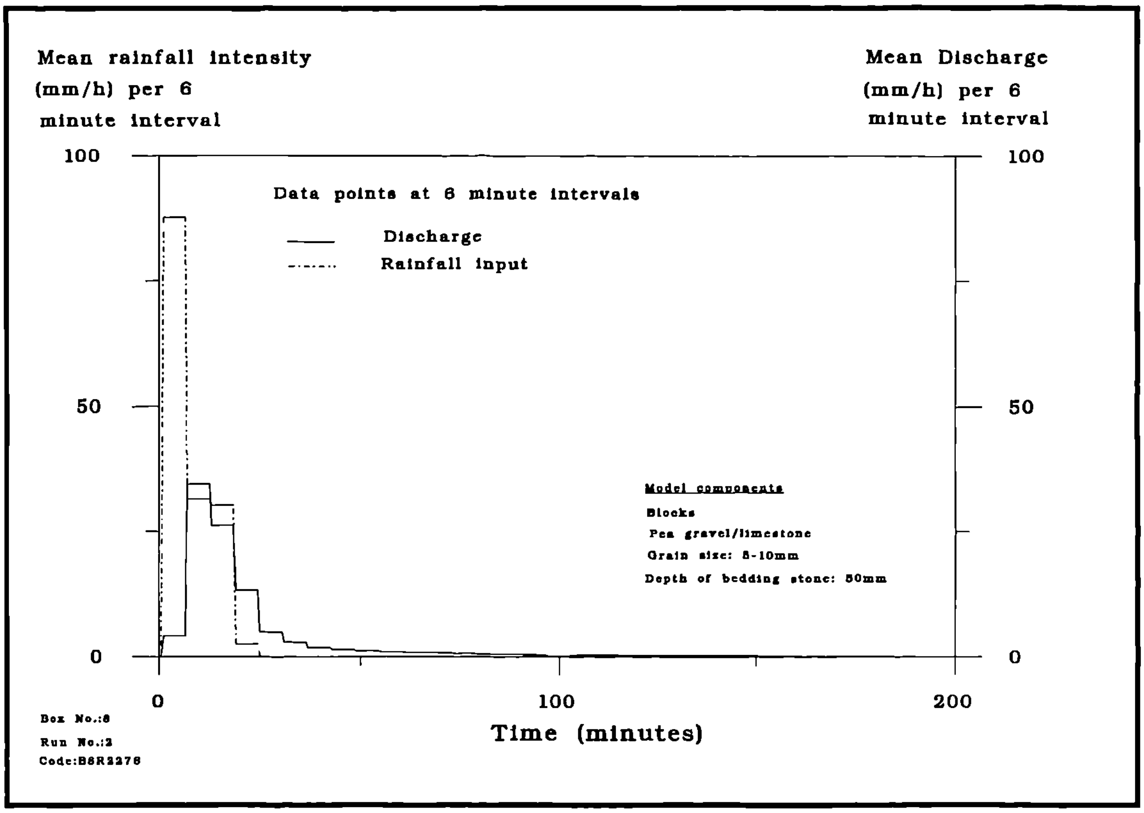


Figure 5.6 Hydrograph and hyetogram for Box 8 Run 2.

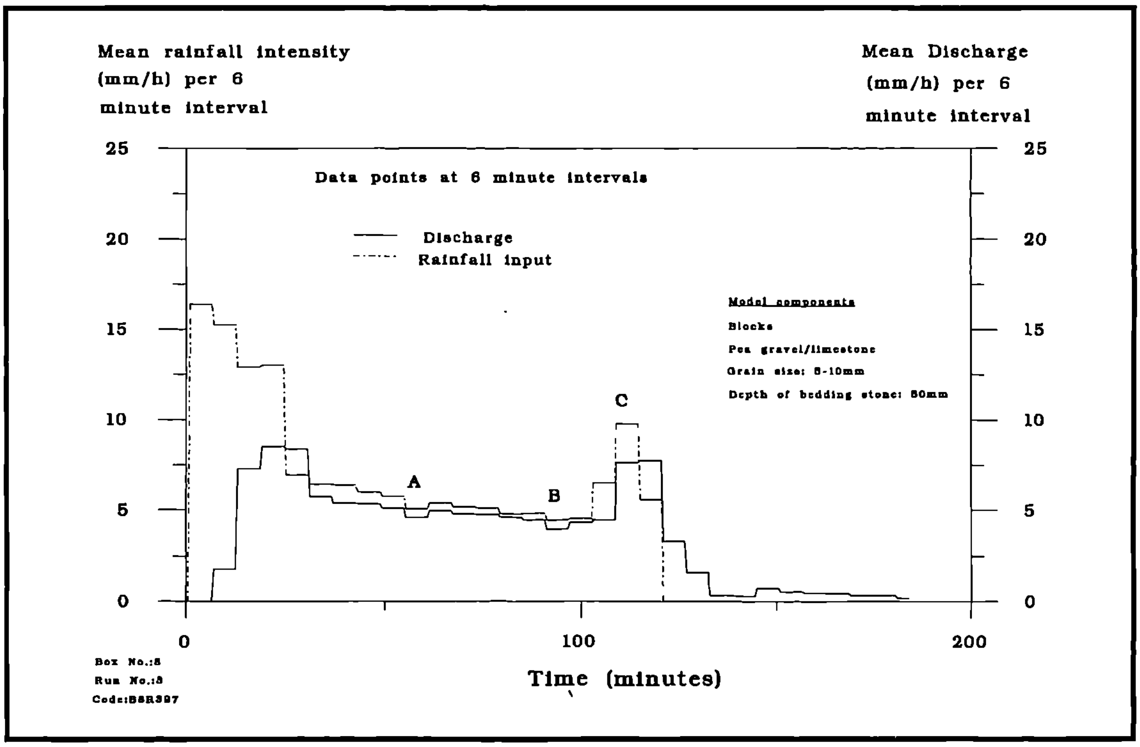


Figure 5.7 Hydrograph and hyetogram for Box 8 Run 3.

The hydrograph shows that drainage continues for up to 60 minutes after rainfall ceases. For the 30 mm h^{-1} rainfall event, the lag in response, or wetting phase was very short (Figure 5.6). This may be explained by two factors; first, the addition of a greater volume of rainfall in a shorter time and, secondly, the fact that the structure contained water from the previous event which will inevitably reduce the time necessary for the wetting of the structure. The response of the hydrograph is more rapid and maximum discharge (drainage) is greater than in the previous simulation. It is suggested that the response of the hydrograph is more obvious due to the greater volume of rainfall applied over a shorter storm duration.

The response to variations in rainfall intensity is also shown in Figure 5.7 which plots the hyetogram and hydrograph for the 7.5 mm h^{-1} rainfall event. Once drainage begins, the response of the hydrograph mirrors that of rainfall intensity, especially if rainfall intensity temporarily increases or decreases. This can be seen at points A, B and C (Figure 5.7). The greater rainfall intensity at point C produces a dramatic increase in discharge, which is similar to the discharge response of the 30 mm h^{-1} rainfall event.

On examination of Figures 5.5 to 5.7, a visual difference is apparent in the drainage characteristics of the same model box under varying rainfall intensities. A shorter duration rainfall simulation with a higher rainfall intensity (Figure 5.6) produces a more peaked drainage hydrograph, whereas a longer rainfall duration with a lower rainfall intensity produces a more rectangular hydrograph shape (Figure 5.7). It is therefore concluded that drainage characteristics are closely influenced by rainfall intensity once drainage commences.

5.2.2. Do structural components influence discharge response ?.

To discuss this question, the discharge response during the 15 mm h^{-1} event for three separate boxes have been chosen for comparison. The boxes chosen were Box 1, containing only pea gravel (1-10 mm) (Figure 5.8); Box 5 containing surface blocks and pea gravel (5-10 mm) (Figure 5.9); and Box 7 containing surface blocks and pea gravel (1-3 mm) (Figure 5.10). The hydrograph response to rainfall input for model Box 1 (Figure 5.8) shows little lag in response with the hydrograph fluctuating in response to changes in rainfall intensity. This hydrograph also shows a second peak in discharge at point A. This effect was associated with water displacement due to the box being raised during the weighing process (see section 3.2.8). If Figure 5.8 and Figure 5.9 are compared, a different response in the hydrographs for the 15 mm h^{-1} rainfall event is apparent. Figure 5.9 (Box 5 containing surface blocks and pea gravel) has a greater lag in drainage response to rainfall. Furthermore, the volume of water drained was lower. This may suggest that the presence of surface blocks produces an increase in the time lag between rainfall input and discharge output. However, this is only a visual comparison and a quantitative analysis of discharge response is undertaken in section 5.3.4.

A second variable in the structural components was the size of bedding material. For example, Box 5 contained pea gravel 5-10 mm and Box 7 contained pea gravel 1-3 mm. If Figures 5.9 and 5.10 are compared for Boxes 5 and 7 respectively, a different hydrograph response for each box is visible. Box 7 has a much longer lag time (or wetting phase) before discharge begins and the volume of discharge is significantly lower.

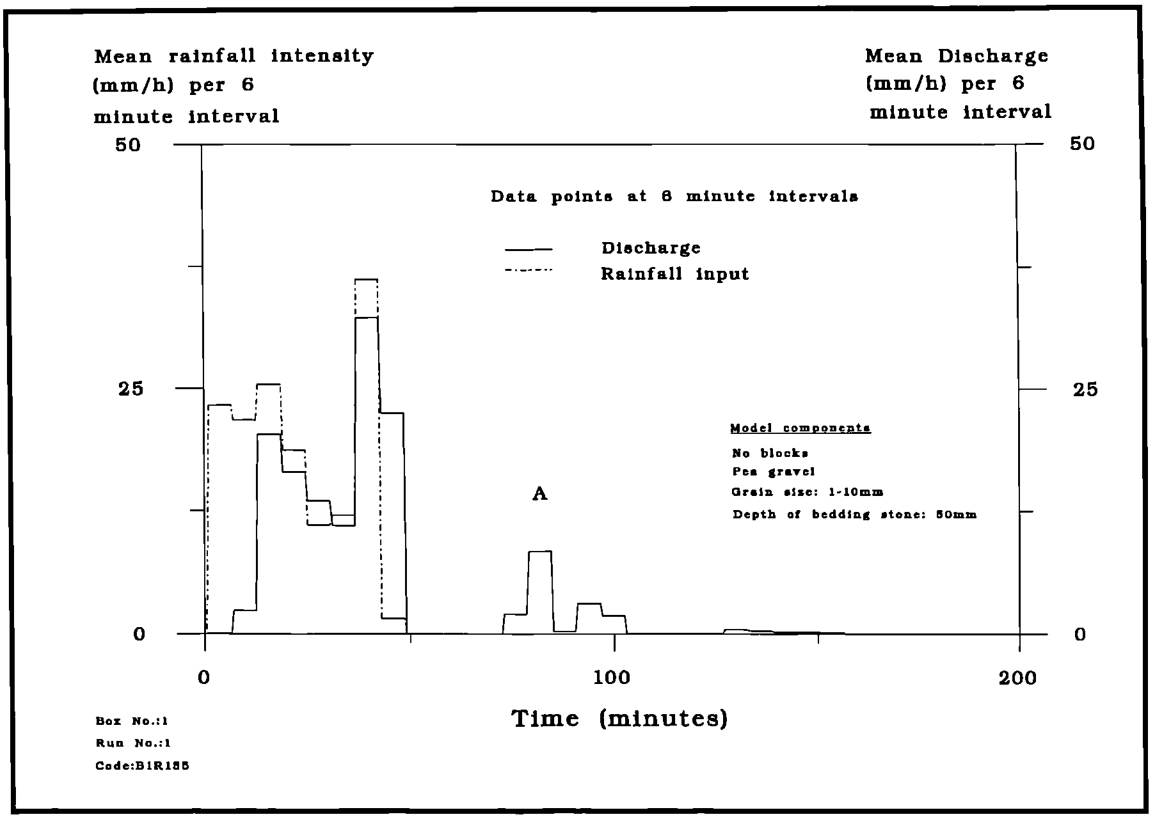


Figure 5.8 Hydrograph and hyetogram for Box 1 Run 1.

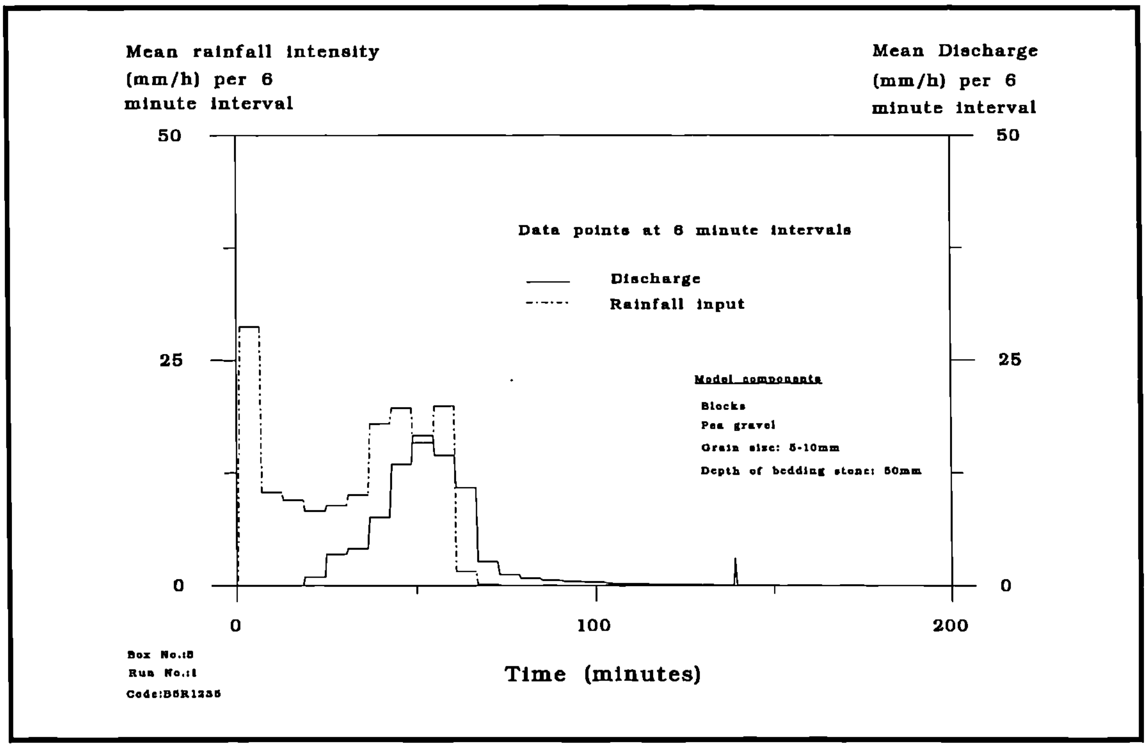


Figure 5.9 Hydrograph and hyetogram for Box 5 Run 1.

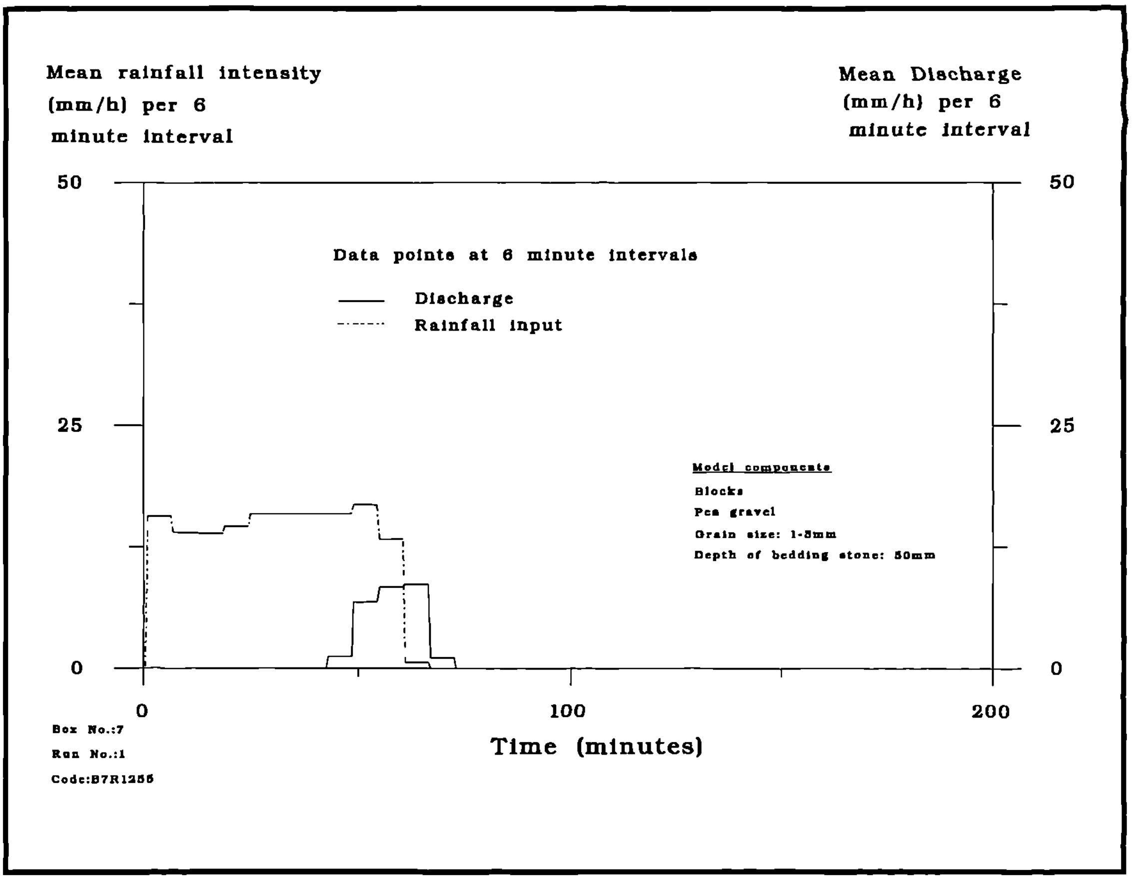


Figure 5.10 **Hydrograph and hyetogram for Box 7 Run 1.**

This phenomenon is directly attributable to the structural components since Box 7 contained the smaller pea gravel which had a higher specific surface area for retaining water (Chapter 4). A higher specific retention leads to a reduction in the total discharge from the structure and an increase in the length of the wetting phase. From Figures 5.8 to 5.10, it can be seen that the arrangement of the structural components influence discharge response. The degree to which the structure influences the response is significant and will be quantified and discussed in Section 5.3.3. The model box containing both surface blocks and the smaller grain size of bedding material seems to have the greatest specific retention and the greatest attenuating effect on drainage.

5.3 Box Discharge response.

The hyetogram and hydrograph analysis showed that discharge was influenced by both rainfall intensity and the car park structure. In section 5.2.1 pre-storm retention was suggested to have a significant influence on the wetting phase and, consequently, on the lag time. The analysis in section 5.2 provided a graphical comparison. In this section a quantitative analysis is performed in order to isolate the influence of rainfall intensity, car park structure and pre-storm retention on behaviour.

The discharge (mm) 2 hours after the cessation of rainfall was measured during each experiment. Discharge ceased within 2 hours after a rainfall simulation and the outlet valves from the base of the model car park structure were closed. Table 5.2 gives the total discharge for all boxes following each rainfall simulation having allowed time for complete drainage.

Table 5.2. Total Discharge following each rainfall simulation the model boxes.

	Run 1	**Run 2**	**Run 3**
Box number	**Total discharge (mm)**	**Total discharge (mm)**	**Total discharge (mm)**
1 (no blocks)	12.06	12.03	11.61
2	5.89	8.28	13.33
3	5.93	8.52	14.25
4	7.02	9.84	11.87
5	7.81	9.49	11.64
6	7.30	10.01	11.00
7	2.59	6.26	9.36
8	7.09	9.26	11.81
9	9.05	11.00	11.11
10	8.01	10.02	11.64

Runs 1, 2 and 3 had target rainfall intensities of 15 mm h^{-1}, 7.5 mm h^{-1} and 30 mm h^{-1} respectively. The data of Table 5.2 show two patterns. First, all boxes containing surface blocks showed an increase in the discharge following each successive rainfall simulation. Secondly, the discharge varied from box to box (during each set of rainfall intensity experiments) which indicated an effect of the structural components on discharge response.

There may be two factors influencing the increase in discharge over consecutive rainfall events. These are variations in rainfall intensity and the pre-storm retention volume.

5.3.1 Increases in discharge due to variations in rainfall intensity.

In Chapter 4, it was shown that the duration of water contact with the surface blocks influenced the rate of water absorption (shorter contact producing lower absorption volumes). This characteristic would also influence the discharge from the model car park. If rainfall intensity was solely responsible for controlling variations in discharge over consecutive events, the shortest storm duration (Run 2) would be expected to produce the greatest total discharge response, since absorption by the surface blocks would be lower. This is, however, not the case.

Furthermore, if rainfall intensity increased or decreased a difference in drainage volume would be expected, since storm duration also influences retention. For example if it is assumed that a 15 mm h^{-1} event produces a discharge of 100% then an increase in rainfall intensity to 30 mm h^{-1} should produce a consistent percentage increase from the 15 mm h^{-1} event.

The drainage volume from the 15 mm h^{-1} rainfall event on all of the boxes was assumed to be a response of 100%. The difference in drainage volume from each run and box were calculated as a percentage of the difference from the first 15 mm h^{-1} event. Table 5.3 gives the percentage differences from the first rainfall simulation. The percentage differences vary significantly between Runs 2 and Run 3 for each box. For a shorter storm duration (Run 2) a greater drainage volume would be expected, which is indeed the case.

However, for a longer storm duration (Run 3), the drainage volume would be expected to be lower due to a greater water contact time for block absorption. This is not the case, suggesting that variations in total output could not be attributed solely to the difference in rainfall intensity.

Table 5.3. The percentage difference from the discharge after Run 1 for all boxes after Run 2 and 3.

Box number	Run 2	Run 3
	Percentage difference from Run 1	Percentage difference from Run 1
1	0	-4
2	41	126
3	44	140
4	40	69
5	22	49
6	37	51
7	142	261
8	31	67
9	22	23
10	25	45

5.3.2 The effect of pre-storm retention.

The model boxes in the first rainfall simulation were laboratory dry and the pre-storm retention was assumed to be zero. The increase in total discharge can in part be explained by the fact that Run 2 was carried out on boxes which were not dry and retention had not returned to the pre-storm level of the first rainfall simulation (Run 1).

Pre-storm retention volumes are given in Table 5.4. If pre-storm retention amounts were high, it might be expected that the total discharge would increase in direct proportion to retention. All boxes showed an increase in pre-storm retention between Run 2 and Run 3. This would explain the increases in the percentage differences given in Table 5.3. Pre-storm retention significantly influences the discharge over consecutive rainfall events, therefore producing a greater discharge.

Table 5.4. Pre-storm retention in each model box prior to Runs 2 and 3.

Box number	Pre-storm retention prior to Run 2 (mm)	Pre-storm retention prior to Run 3 (mm)
1	0	0
2	4.83	7.39
3	5.03	7.41
4	5.36	6.91
5	3.37	6.07
6	4.08	6.61
7	5.52	10.12
8	3.57	6.89
9	2.53	5.11
10	5.31	6.00

5.3.3 Variations in Box discharge response due to box components.

Table 5.2 showed that there were significant differences in total discharge between each model box. In order to reduce the effect of other factors on discharge (ie. pre-storm retention and rainfall intensity), the 15 mm h^{-1} rainfall simulation will be examined in order to explain the influence of structural components on total discharge. Table 5.5 gives the model box components for each box and Figure 5.11 shows the total discharge for all boxes after the 15 mm h^{-1} rainfall event. It can clearly be seen that Box 1 (pea gravel only) discharged the greatest volume of water (12.10 mm equivalent depth of rainfall), which may be explained by the absence of surface blocks. Boxes 5, 6 and 7 exhibited differing discharge amounts even though the depth of bedding material was the same (see Table 5.5). The grain size of bedding material in these boxes differed being: 5-10 mm, 3-5 mm and 1-3 mm, for Boxes 5, 6 and 7, respectively. This suggests that, with a larger grain

Table 5.5. Components held within each model box.

Box number	Type of bedding material	Depth of bedding material (mm)	Grain size of bedding material (mm)
1	Pea gravel	50	1-10
2	Pea gravel	50	1-10
3	Pea gravel	30	1-10
4	Pea gravel	70	1-10
5	Pea gravel	50	5-10
6	Pea gravel	50	3-5
7	Pea gravel	50	1-3
8	Pea gravel Limestone	25 25	5-10
9	Pea gravel limestone	30 40	5-10
10	Limestone	50	5-10

size of bedding material, the discharge from the model boxes will be greater due to a lower specific surface area in comparison to the smaller grain-sized bedding material. Apart from the presence of blocks, the difference in grain size of bedding material held in a model box had the most significant effect on water discharge during the 15 mm h^{-1} rainfall events.

A second structural variable was the type of bedding material. Box 8, for example, contained 50% pea gravel and 50% limestone with a depth of sub-matrix similar to Box 5. Box 5 discharged slightly more water than Box 8 (7.81 mm compared with 7.09 mm), but

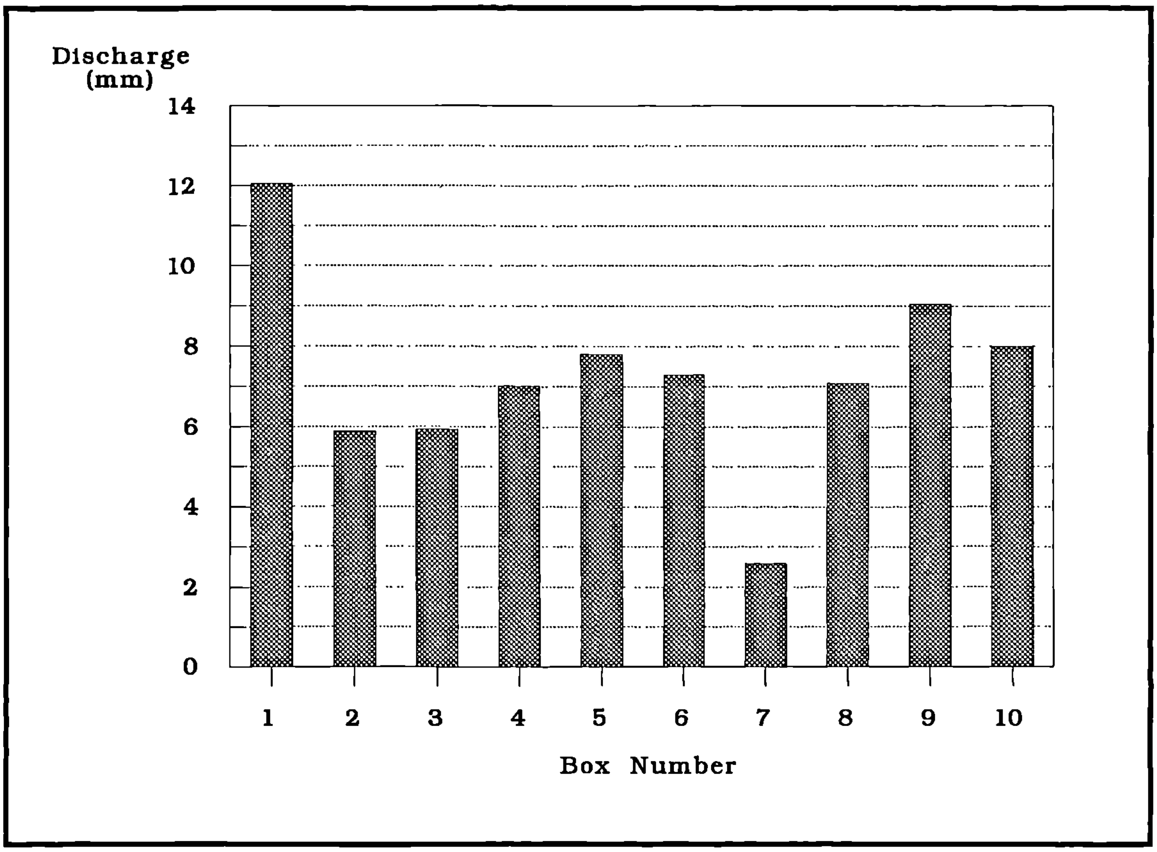


Figure 5.11 **Total discharge from all boxes after Run 1.**

discharges from these two boxes varied over each rainfall simulation (being influenced by the pre-storm retention characteristics). Box 9 had a pea gravel/limestone mix of 43% and 57%, respectively, with a depth of sub-matrix similar to Box 4, but Box 9 had the second highest discharge. These results suggest that the type of sub-matrix, it's size and it's shape influence the total discharge, in that the boxes containing pea gravel discharge less than those containing limestone. The total discharges ranged from 2.59 - 12.06 mm, which is between 17% and 80% of the rainfall applied.

5.3.4 Attenuation of discharge response.

The previous section demonstrated how structural components and pre-storm retention both influenced total drainage over consecutive rainfall simulations. It was shown that rainfall intensity (section 5.2) pre-storm retention and the structural components influenced the length of the wetting phase, and consequently, the drainage volume.

When constructing a car park to attenuate discharge, prior knowledge of which structural components produce the slowest drainage (and thus attenuation) is required. It has already been shown that the analysis is complicated by pre-storm retention and rainfall intensity. This analysis will concentrate on the lag time in discharge response during Run 1 on all boxes.

The lag times for the 15 mm h^{-1} rainfall simulations were calculated for each box and are given in Table 5.6. Box 7 had the greatest lag time and Box 1 the shortest. Box 7 had a smaller grain size of bedding material with a larger specific surface area and, consequently, a larger surface area to retain infiltrating water, thus producing a slower discharge

Table 5.6. **Lag times for all boxes during the 15 mm h^{-1} events.**

Box number	Lag time (minutes)
1	1.8
2	7.2
3	22.8
4	22.8
5	20.4
6	27.0
7	46.2
8	25.8
9	20.4
10	15.6
Average	21.0

response. A smaller grain size of bedding material produces a longer lag time. For example the two boxes containing the smallest grain size bedding material had the greatest lag times; ie. Box 7 contained pea gravel with a grain size of 1-3 mm and Box 6 contained pea gravel with a grain size of 3-5 mm. The presence of surface blocks also influences the lag time.

Box 1 contained only pea gravel and no surface blocks and had the shortest lag time. In order to produce a slower drainage response, a car park structure should be constructed with surface blocks and a small grain-sized bedding material (1-3 mm).

5.4 Specific retention

Retention within the model car park was calculated by subtracting the discharge from the rainfall input (Table 5.1). Retention is a function of discharge, rainfall input, pre-storm retention and structural components. These variables will influence retention in the opposite way that they affect discharge, eg. pre-storm retention will result in a decrease in rainfall retention over consecutive rainfall events and the presence of smaller sized bedding material and surface blocks will increase retention capabilities. The retention of water by the model car park structure will be discussed in more detail in the next chapter. However, this section will examine retention characteristics after each rainfall simulation to ascertain whether the surface blocks and/or the bedding material influences retention over consecutive events. This section also discusses whether it is possible to predict block retention over consecutive events.

In Chapter 4 it was shown that the bedding material had a maximum retention value which was reached soon after wetting. However, if Table 5.7 is examined, it is seen that the total retention within the model boxes increases over successive rainfall events. Box 1 did not contain surface blocks and showed only a slight increase in specific retention over consecutive rainfall events. It is therefore suggested that this increase in total retention is associated predominantly with the surface blocks. This conclusion is substantiated by the findings from the experiments detailed in Chapter 4 which showed that the retention by the surface blocks was strongly influenced by the length of the contact time with water. To examine this further, data were analyzed from experiments on a model car park which contained only surface blocks. There were two stages in the experimental procedure. The first stage involved three rainfall simulations with each rainfall simulation being 24 hours apart. These were then left to dry for a period of approximately 2 months (1532 hours) before the second phase of the experiment. Table 5.8 shows the total retention, the inter-rainfall period and the pre-storm retention before each subsequent rainfall simulation.

<u>Table 5.7.</u> Total water retention in the model car park over three rainfall simulations.

Box	Retention after Run 1 (mm)	Retention after Run 2 (mm)	Retention after Run 3 (mm)
1 (no blocks)	2.94	2.97	3.65
2	9.11	11.64	12.76
3	9.07	11.51	12.23
4	7.98	10.52	10.22
5	7.19	8.88	9.45
6	7.70	9.07	10.64
7	12.41	14.65	15.76
8	7.91	9.08	10.08
9	5.95	7.12	9.19
10	6.99	8.56	9.40

<u>Table 5.8.</u> Retention characteristics of a model car park structure containing surface blocks.

Stage 1	Cumulative retention (mm)	Inter-rainfall dry period (hours)	Pre-storm retention (mm)
Run 1 (Dry Box)	3.44	0	0.00
Run 2	5.25	24	2.67
Run 3	6.57	24	4.54
Stage 2			
Run 4	5.33	1.532	2.86
Run 5	6.79	71	4.11
Run 6	7.12	22	5.60
Run 7	7.26	22	6.08

Figure 5.12 shows the pre-storm retention before each rainfall simulation and the retention after each event. The pattern of retention is very similar, indicating that the pre-storm retention has a strong influence on the total retention after a simulation. The total retention increase over Runs 1 to 3 and over Runs 4 to 7. Evaporation would have taken

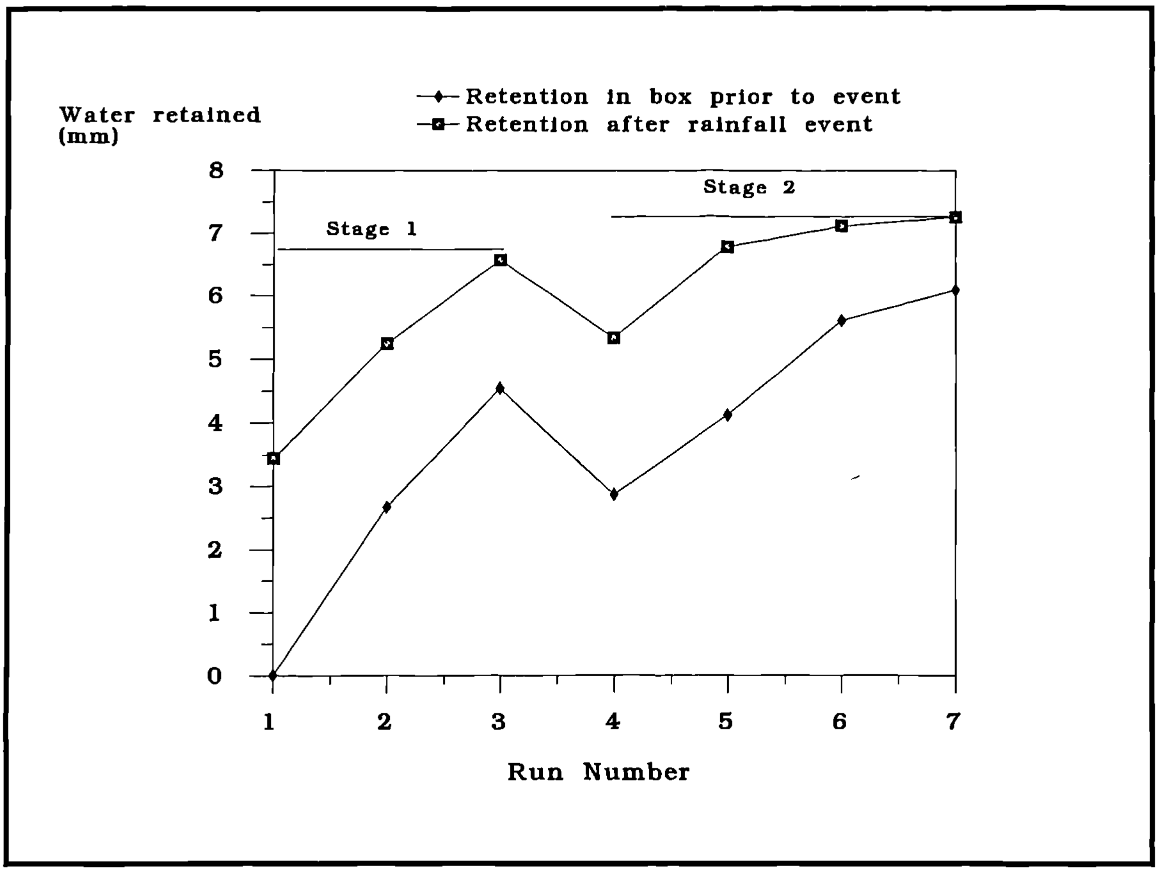


Figure 5.12 **Pre-storm retention and total retention over 7 consecutive runs on a box containing surface blocks.**

place between the two stages of the experiments (between Run 3 and Run 4). This explains the lower pre-storm retention value for Run 4.

The retention after Run 4 is of a similar magnitude to Run 2 even though the retention for Run 3 was higher. This suggests that the blocks can only retain a certain amount of water per simulation and contact with water does not guarantee a return to maximum retention. It is as if the blocks absorb water during contact and then, depending on pre-storm retention and water contact time, they have a certain retention capacity. For example, for Runs 2 and 4, the water contact time and pre-storm retention were similar for both events and the resultant retention was also of a similar magnitude. Run 4 had 0.19 mm more pre-storm retention than Run 2 and the model car park retained 0.08 mm more water than Run 2 after Run 4. This suggests that the model car park surface responds in a predictable fashion depending on pre-storm retention and water contact time.

From the experiments discussed in Chapter 4, it was shown that:

1) water absorption is strongly influenced by contact time with water and can best be described by Equation 4.4.

2) water absorption by the blocks is influenced by pre-storm retention.

Estimates of water retention were calculated using these data. Three types of predictions were made using different assumptions and are given in Table 5.9. The predicted results were then compared to the actual retention values of the model car park structure which were given in Table 5.8. The percentage differences were also calculated.

Prediction 1

The first prediction assumes that water retention is solely governed by the contact time with water. The contact time with water is the cumulative contact time (column B). The retention is then calculated using Equation 4.4 and the cumulative contact time is substituted into the equation as (t).

Prediction 2

This prediction uses the single storm duration time in Equation 4.4 (storm duration from column A) and then sums the result with the pre-storm retention. This equation assumes absorption takes the same form even though the blocks have a pre-storm retention greater than zero.

<u>Table 5.9.</u> Actual and predicted (P) retention by a model car park containing only surface blocks.

	A	B	C	D	E	F	G	H	I
Run	Storm length (hours)	Total water contact time (hours)	Actual retention in model box (mm)	P 1 mm	Percentage difference	P 2 mm	Percentage difference	P 3 mm	Percentage difference UNDER-ESTIMATION
1	0.5	0.5	3.44	2.88	-16.28	2.88	-16.28	2.88	-16.28
2	1.0	1.5	5.25	3.77	-28.19	6.11	16.38	3.70	-29.52
3	2.0	3.5	6.57	4.45	-32.37	8.54	29.99	7.87	-25.88
4	1.0	4.5	5.33	4.65	-12.76	6.30	18.20	3.76	-29.46
5	1.0	5.5	6.79	4.80	-29.31	7.55	11.19	4.40	-35.20
6	1.0	6.5	7.12	4.95	-34.48	9.04	26.67	5.65	-20.65
7	1.0	7.5	7.26	5.06	-30.30	9.52	31.31	6.11	-15.84
Average					**-27.90**		**22.31**		**-26.09**

Prediction 3

This prediction uses Equation 4.4 and data on pre-storm retention but it assumes that absorption is slower if the blocks have a pre-storm retention of greater than zero. Retention is calculated by firstly inversing Equation 4.4 to ascertain the equivalent time value for the pre-storm retention, i.e.:

(PSR (g) / 18) = 68.8 + 37.04 .log(t) **Equation 5.1**

(PSR (g) / 18) - 68.8 = 37.04 .log(t)

((PSR (g) / 18) - 68.8) / 37.04 = .log(t)

then inverse log(t) = t

where PSR = pre-storm retention (g), t= time (h).

The pre-storm retention is given in grams and divided by 18 since Equation 4.4 is for a single block and there are 18 blocks per model box structure. The (t) value, in hours, is then added to the storm duration (column B) and this then becomes the new value of (t), which is substituted into Equation 4.4, and the retention is re-calculated for a model box. On examination of Table 5.9 it can be seen that the percentage differences are very different between each prediction, i.e, predictions 1 and 3 under-estimated the retention and prediction 2 over-estimated the block retention by over 20%. If no consideration is made in Equation 4.4 of pre-storm retention, i.e., as in prediction 2, the retention is over-predicted by an average of 22%. The percentage difference over-estimation increases for prediction 2 over consecutive rainfall events. This suggests that the accuracy of the prediction decreases, possibly because the blocks have a slower rate of absorption if they are approaching saturation. Therefore, even though the percentage difference may be on average lower for prediction 2, it's accuracy decreases over successive rainfall events. Unfortunately, the experiment did not continue long enough to ascertain if the accuracy of the prediction decreased significantly with a larger number of consecutive rainfall simulations.

Prediction 1 under-estimated the block retention by an average of 27.9%, which was marginally higher than prediction 3. The percentage difference for prediction 3 began to decrease by approximately 5% over each of Runs 5, 6 and 7. This suggests that the accuracy of the predictions improves over successive rainfall events. However, prediction 3 would seem to be a more realistic description of the process by which absorption occurs, i.e., pre-storm retention influences the rate of absorption by producing a slower absorption rate if the pre-storm retention is higher.

It is suggested from the above analysis that a consideration of pre-storm retention should be included in the calculation of retention (e.g., prediction 3). The under-prediction here may be a function of a scaling error, since Equation 4.4 is based on the behaviour of a single block, whereas the model box contained 18 blocks. The greater retention in the model box may also be attributed to some surface retention by the geo-textile; the steel mesh; the box itself; or capillary forces acting between blocks and between the blocks and box sides. These, however, are difficult to quantify but a consideration could be incorporated into the prediction of retention in a model box. For example, a box retention value, eg 1 mm, may be added.

During the short-term hydrological analysis described above, retention was seen to be strongly influenced by pre-storm retention and the box structure. The retention increased over consecutive events and this can be explained by the presence and characteristics of surface blocks whose retention is also influenced by pre-storm retention and contact time with water. The process of retention by the blocks is a complex process and difficult to quantify. However, it is suggested that the absorption processes are similar to the processes described when producing prediction 3 (Equation 5.1).

5.5 Summary of the short term hydrological performance.

5.5.1 Hyetograms and hydrographs

The hydrograph and hyetogram analysis showed that rainfall intensity influenced the shape of the hydrograph with a higher rainfall intensity producing a more peaked hydrograph response. The structural components in the model boxes also influenced the shape of the hydrograph by influencing the total drainage volume and the length of the wetting phase. It was shown that the presence of surface blocks and a small grain-size bedding material (1 - 3 mm) had the greatest attenuating effect on drainage.

5.5.2 Box discharge response

The quantitative analysis on drainage volumes showed that rainfall intensity was not the only factor influencing discharge. Pre-storm retention and box structural components significantly influenced the total drainage over consecutive rainfall events. Variations in bedding material types and sizes and the presence of surface blocks, influenced the total volume of water discharged as well as the attenuation in discharge response.

5.5.3 Specific Retention

Pre-storm retention and the variations in structural components were the most significant influencing factor governing specific retention volumes. Increases in the volume of specific retention over consecutive rainfall events were attributed to the behaviour of surface blocks. A comparison of techniques to predict block retention (using Equation 4.4) showed that a consideration of pre-storm retention was necessary to model block retention processes effectively.

The next chapter examines the long term hydrological performance of the car park structure and considers evaporation processes in some detail.

Chapter 6 -Long-term Hydrological Behaviour of the Structure

6.1 Introduction

This chapter examines the long-term hydrological performance of the car park structures. The analysis deals with the performance between consecutive rainfall events and considers both evaporation and changes in retention. An analysis of the long-term retention patterns will be given first, followed by an analysis of long-term evaporation rates.

6.2 Long-term Retention

6.2.1 Single Storm Retention and Cumulative Retention.

In Chapter 5, the proportion of rainfall retained by the structure during consecutive rainfall events was shown to decrease because of the pre-storm retention in the blocks and bedding material.

Table 6.1. shows the decrease in retention following single rainfall events for the first three runs (15, 30 and 7.5 mm h^{-1} respectively) on the model boxes (Column F Table 6.1). Box 1 dried out during the inter-rainfall dry periods and did not have any pre-storm retention level until the beginning of the fourth simulation (see Figure 6.1). Box 4 showed a decrease in retention during the second storm. This was because the second storm received only 1.8 mm of rainfall before equipment failure. This rainfall event was re-simulated as Run 3 (which has the same rainfall application as Run 2 for the other boxes).

Table 6.1. Hydrological data from all boxes for all rainfall simulations.

A	B	C	D	E	F	G
Box	Run	Length of storm-hours	Total rainfall (mm)	Total Drainage (mm)	Retention of rainfall during individual event (mm)	Total cumulative retention held within the structure (mm)
1	1	1	15.00	12.06	2.94	2.94
	2	0.5	15.00	12.03	2.97	2.97
	3	2	15.26	11.61	3.65	3.65
	4	10	50.00	46.02	3.98	4.13
2	1	1	15.00	5.89	9.11	9.11
	2	0.5	15.09	8.28	6.83	11.64
	3	2	15.00	13.33	5.37	12.76
	4	3	29.17	23.94	5.22	11.88
3	1	1	15.00	5.93	9.07	9.07
	2	0.5	15.00	8.52	6.48	11.51
	3	2	15.11	14.25	4.82	12.23
	4	3	27.78	23.23	4.54	11.35
4	1	1	15.00	7.02	7.98	7.98
	2 *	0.15	1.80	0.01	1.79	6.09
	3	0.5	15.00	9.84	5.16	10.52
	4	2	15.18	11.87	3.31	10.22
	5	3	27.78	22.85	4.93	10.51
5	1	1	15.00	7.81	7.19	7.19
	2	0.5	15.00	9.49	5.51	8.88
	3	2	15.03	11.64	3.38	9.45
	4	3	27.78	22.71	5.07	10.30
6	1	1	15.00	7.30	7.70	7.70
	2	0.5	15.00	10.01	4.99	9.07
	3	2	15.03	11.00	4.03	10.64
	4	3	27.78	21.52	6.26	11.20
7	1	1	15.00	2.59	12.41	12.41
	2	0.5	15.39	6.26	9.13	14.65
	3	2	15.00	9.36	5.64	15.76
	4	3	27.78	19.24	8.54	18.34
8	1	1	15.00	7.09	7.91	7.91
	2	0.5	15.47	9.96	5.51	9.08
	3	2	15.00	11.81	3.19	10.08
	4	3	27.78	22.27	5.51	11.51
9	1	1	15.00	9.05	5.95	5.95
	2	0.5	15.59	11.00	4.59	7.12
	3	2	15.18	11.11	4.08	9.19
	4	3	27.78	23.93	3.85	9.16
10	1	1	15.00	8.01	6.99	6.99
	2	0.5	15.33	10.02	5.31	8.56
	3	2	15.04	11.64	3.40	9.40
	4	3	27.78	22.66	5.12	9.68

* Equipment failure occurred during the run, therefore, this event was simulated again in Run 3.

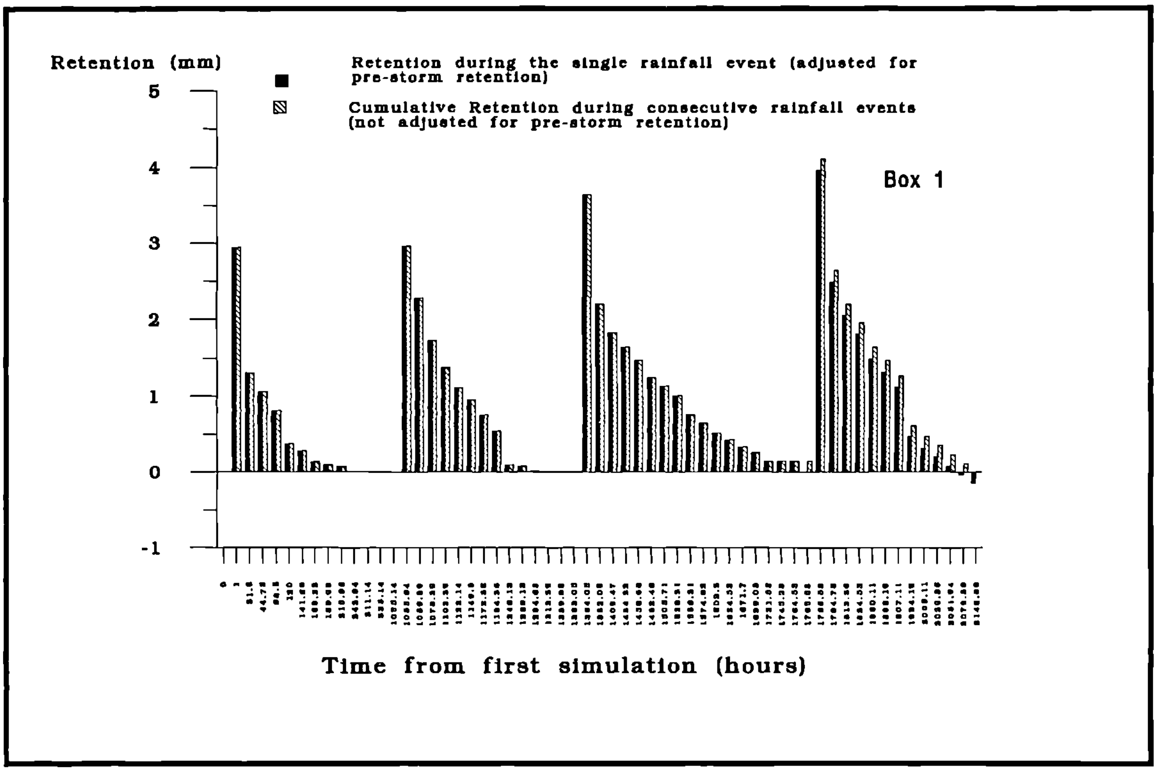


Figure 6.1 **Retention of rainfall by Box 1 during single events. The total volume of water retained in the structure is also shown.**

Figure 6.2 shows the retention from single rainfall events and the cumulative retention (including pre-storm retention) within Box 2 over the whole experimental period. This figure illustrates the general patterns shown by all of the boxes. The second rainfall event shows an increase in the cumulative retention values (i.e., from 9.11 mm to 11.64 mm). Cumulative retention increases again after the third rainfall event to 12.76 mm, but decreases slightly during the fourth simulation to 11.88 mm. The retention after each single rainfall event in Box 2 decreases for the first three rainfall events with the fourth showing similar values to the third (i.e., 5.37 mm in Run 3 and 5.22 mm in Run 4). Figure 6.3, which is a similar plot for Box 6, also illustrates similar patterns. This figure shows that the retention during single rainfall events could sometimes be negative, i.e. just before

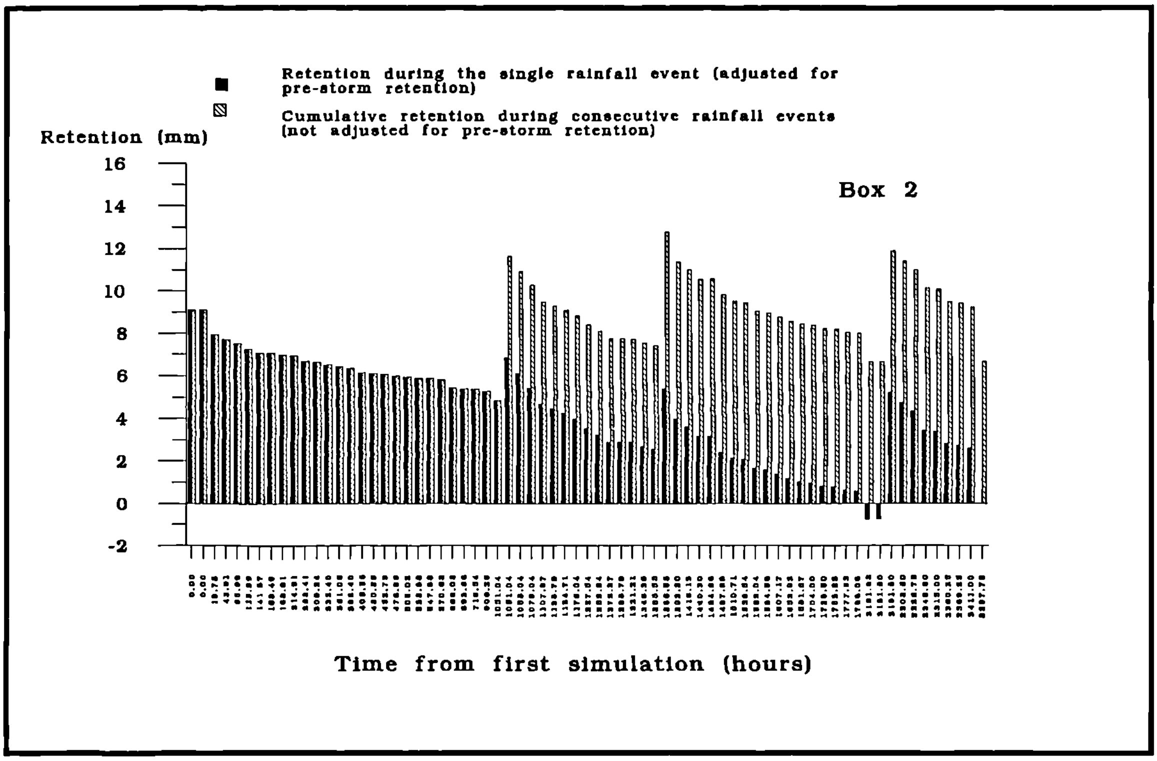


Figure 6.2 Retention of rainfall by Box 2. The total volume of water retained in the structure is also shown.

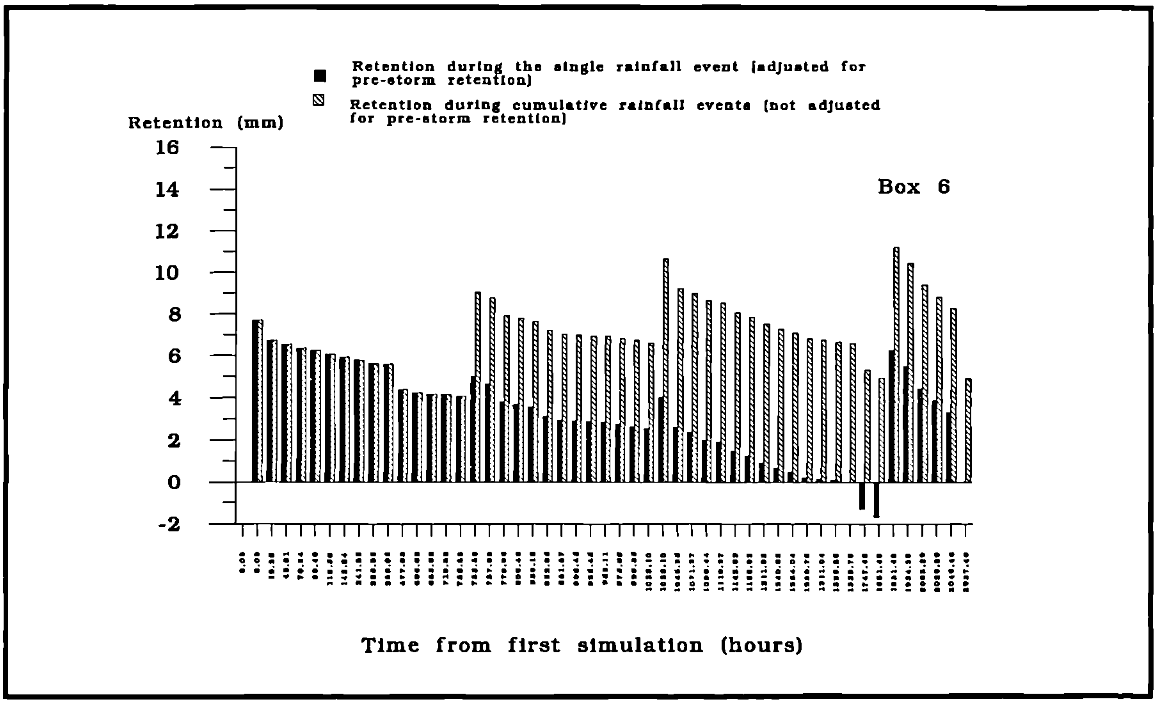


Figure 6.3 Retention of rainfall by Box 6. The total volume of water retained in the structure is also shown.

Run 4. Negative values occurred when the retention associated with the single event was evaporated in the inter-rainfall dry period.

The decrease in retention over consecutive rainfall events can be explained by the total cumulative retention values. All boxes, apart from Box 4 (for reasons discussed above), demonstrated an increase in total cumulative retention over consecutive rainfall events. This increase can be explained by the results given in Chapters 4 and 5, which showed that the contact time between the surface block and rainfall determined the total retention. Thus, with an increased contact time, the retention would increase.

6.2.2. Analysis of long-term retention curves

The retention for each box and run were plotted as in Figure 6.4 which is an example illustrating the retention curves for Box 5 over runs 3 and 4. It is apparent that there are significant changes in the gradients of the retention curves approximately 50 hours after rainfall ended. The retention curves were therefore divided into two segments; the first segment comprised data for the first 50 hours and the second stage comprised data from 50 hours until monitoring ceased. Best fit lines were fitted to the two different segments of each curve. All boxes and runs were analysed and the gradients were obtained from the regression analysis. The regression equation takes the form:

Retention = a - bx **Equation 6.1**

where a and b are constants and x = time (h), and was used in all analysis.

6.2.2.1 Stage I retention analysis.

The gradients of the segment I curves (0-50 hours) were found to be approximately 10 times greater than those of the Stage II curves (50 hours plus). This suggests that a significant change in retention occurred at the end of Stage I. Figure 6.5, shows the various rates of change of retention for the retention curves from segment I and II following the first rainfall simulation on each box. On examination of these gradients for all of the runs and boxes, it was seen that there was a similarity in values with one main exception being Box 1 which had a much higher gradient in the stage I curve. This suggests that water stored in Box 1 is lost by evaporation at a more rapid rate during the initial stage in comparison with the other boxes containing blocks.

6.2.2.2 Stage II retention analysis.

Figure 6.6 gives the gradients calculated from the retention curves for each box for segment II over all rainfall simulations. On examination of Figure 6.6, some distinctive patterns are apparent. For Runs 1 and 2, Box 7 has the steepest slope, which is indicative of a greater rate of water loss by evaporation. Boxes 2 and 3 also have steep gradients, with Box 3 having the greatest value for Run 3. Both boxes contained bedding material with a grain size of 1-10 mm. The gradients are lower in comparison to the other boxes for Boxes 8, 9 and 10 during the first 50 hours. These boxes contained limestone which have a lower evaporation rate during Stage II of the inter-rainfall dry period.

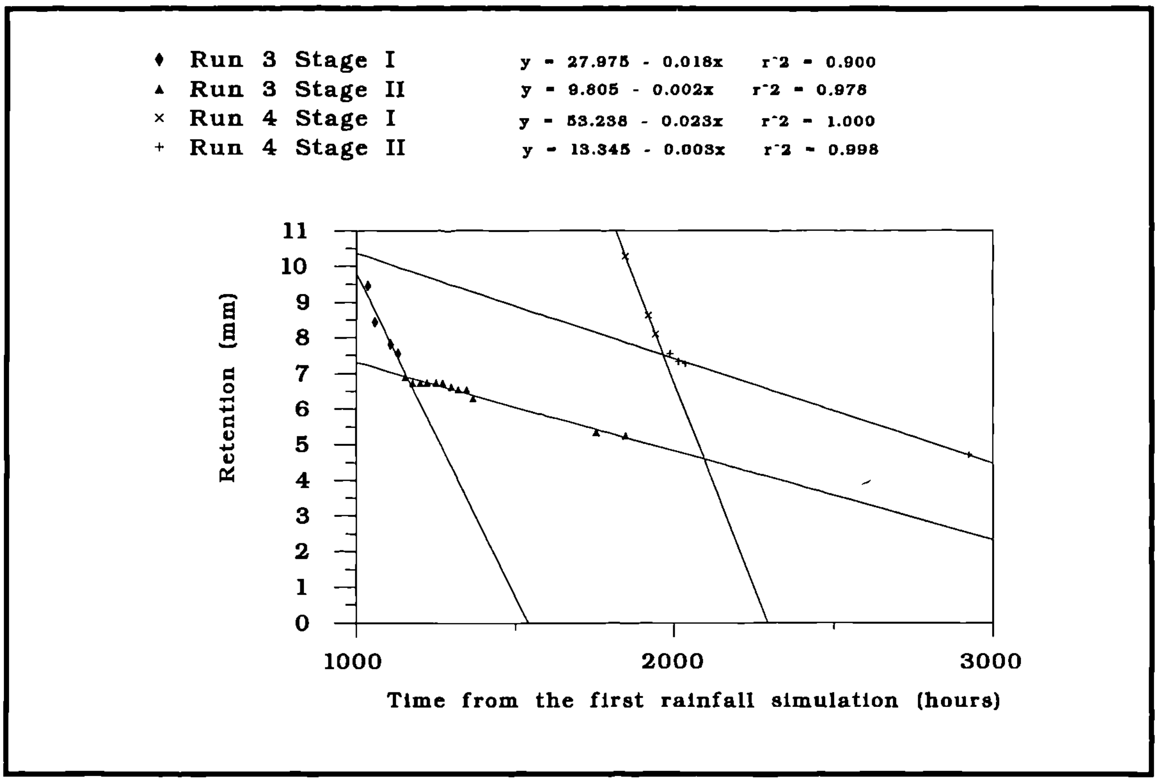


Figure 6.4 Retention by Box 5 during the dry period for runs 3 and 4. Each data set is divided into two segments.

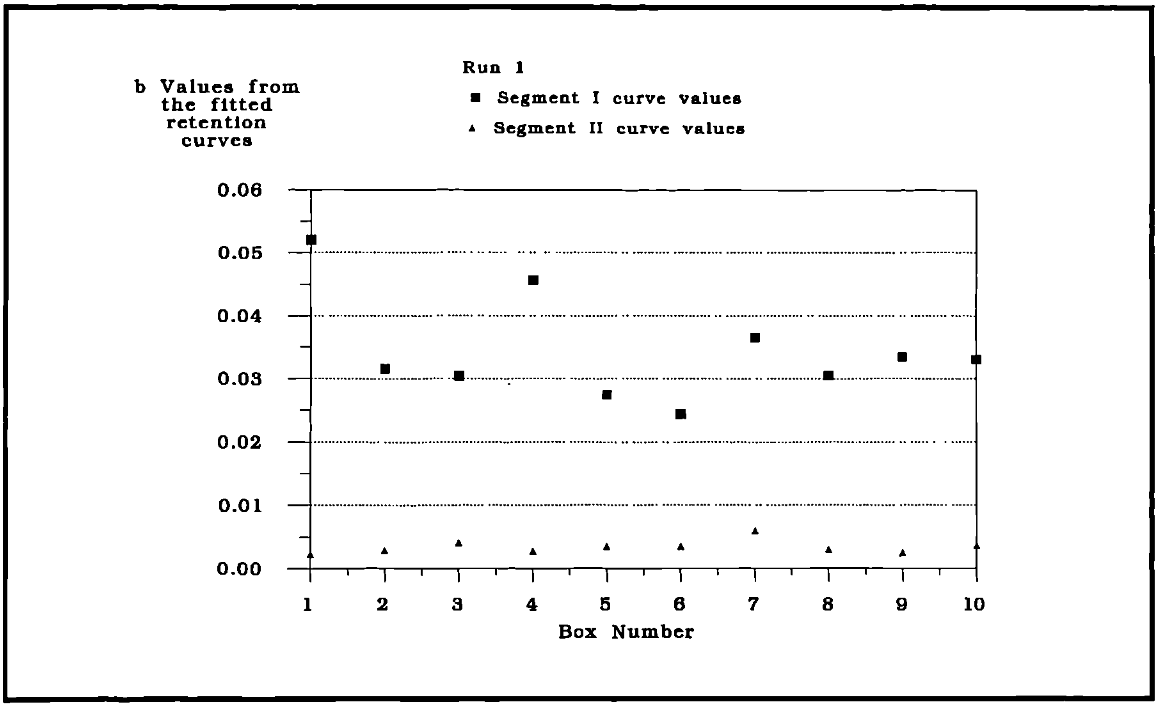


Figure 6.5 b values obtained from the fitted retention curves of all boxes.

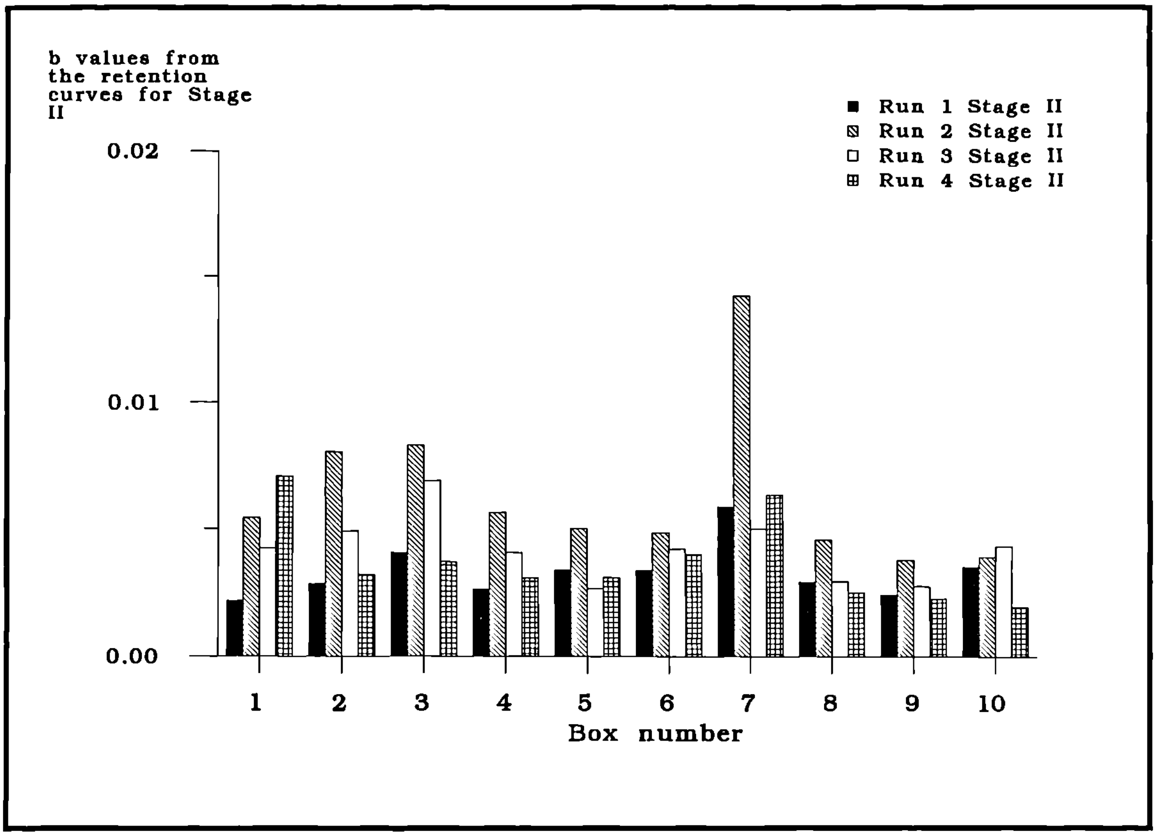


Figure 6.6 b values for the gradient of the retention curves for stage II, all boxes and runs.

In general, the slopes calculated from the retention curves during Stage II of the dry period show little variability (ranging from 0.02 to 0.08; excluding Box 7 Run 2). This indicates that the long-term changes in retention are generally similar for most of the boxes suggesting that long-term evaporation rates are governed more by water availability and the presence of the blocks rather than the characteristics of the bedding material.

6.2.2.3 Summary of retention curve analysis.

It is evident from the above analysis that water loss by evaporation over time takes on a similar form for all of the dry periods, although the actual retention volumes varied significantly. In an attempt to see whether the retention curves from all 4 runs could be indicative of the retention performance of each box, the single box storm retention curves were superimposed onto a single graph (maintaining the retention amounts, but modifying the starting time of the run) to produce a single curve. Two best fit curves were produced for each new graph, again being divided into two stages (Stage I = 0-50 hours and Stage II = 50+ hours). Figure 6.7. shows the b values of the regression equation for the superimposed curves for stages I and II in each box. There were small differences between each box. For example Box 9 (containing limestone) had a low gradient and, therefore, a smaller rate of change in retention for both stages (indicating a slower rate of evaporation). After the initial stage of evaporation, the availability of water becomes a limiting factor, thus the higher the retention values the more the evaporation during the second stage.

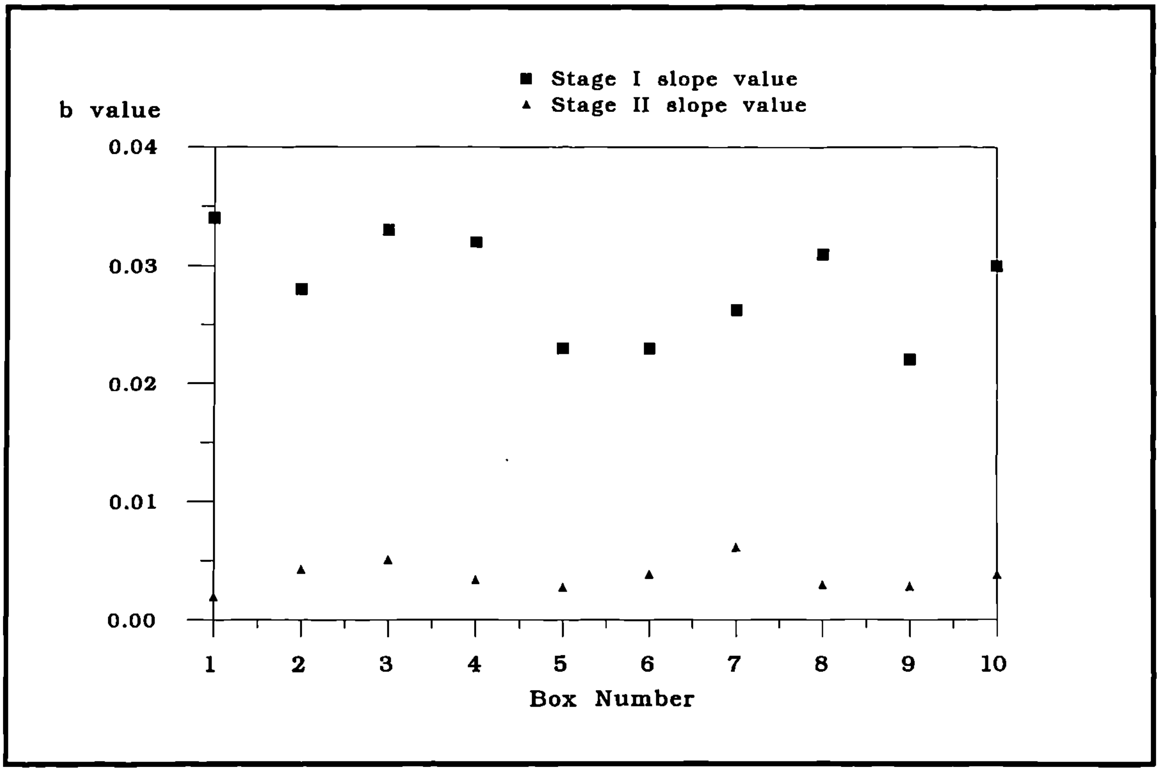


Figure 6.7 The b values for the gradients of the superimposed gradient curves.

During the second stage there was less variation in the rate of water loss, since evaporation amounts were lower due to limited water availability. Box 7 exhibited a higher initial gradient which may be a function of the higher initial retention capabilities of this structure which resulted in a non-supply limited evaporation rate.

6.3 Long-term Evaporation.

Evaporation was calculated from the change in box weight through time after a rainfall event. Since the base of each box was sealed two hours after rainfall ceased, any changes in the overall box weight were assumed to be the result of evaporation. Measurements were usually taken daily during the initial stages of the inter-rainfall dry period (when evaporation values were greater) and at less frequent intervals after a period of two weeks. An evapopan experiment was run concurrently with the hydrological experiments. Evaporation from the structure is an important process to analyze since it will govern the amount of pre-storm retention in the structure before a subsequent rainfall event. This will then influence the discharge and attenuation response of the structure.

6.3.1 The Evapopan Measurements.

The evapopan allowed an analysis of evaporation from an open water body with the same surface area as the model boxes and experiencing the same environmental conditions (air temperature/humidity). These data were compared with model car park evaporation rates and any differences were used to identify the effects that water availability had on box evaporation rates. The evapopan experiment ran for 100 days.

6.3.2 Evapopan - Predictions of evaporation.

Evaporation from an open water body can be predicted from a number of equations. For example, Penman (1948) predicted evaporation using a combination of the two established approaches (energy budget and the mass transfer method) in Equation 6.2:

$$H = E_o + Q \qquad \textbf{Equation 6.2}$$

Where; H = available heat

E_o = is the energy available for evaporation;

Q = is the energy for heating the air.

If net radiation measurements are available, H can be measured directly based on incoming radiation (R_I) and out going radiation (R_o) determined by records on sunshine, temperature and humidity as in Equation 6.3;

$$H = R_I\,(1 - r) - R_o \qquad \textbf{Equation 6.3}$$

where; r = albedo and equals 0.05 for water; R_I is a function of R_A, the solar radiation which is dependent on the ratio of n/N which is the measured sunshine (n) and the maximum possible sunshine (N).

Equation 6.3 uses a number of variables that were not monitored during the experiments (R_I and R_o, n and N). These variables can be estimated from published nomograms to insert into calculations, and are based on meterological field data. Since this study was laboratory based and R_I, R_o, n and N would be difficult to estimate, it was decided that a different approach was needed which would allow an estimate of evaporation based on meterological variables that were measured.

An empirical formula which uses humidity and temperature to estimate evaporation is given by Wilson (1992) (Equation 6.4),

$$E_a=C(e_s-e)f(u) \qquad \textbf{Equation 6.4}$$

where

E_a= evaporation from an open water body

C= an empirical constant

e_s= saturated vapour pressure of air at t °C

e= actual vapour pressure in the air

u= wind speed.

The empirical constants were developed from tests which give the equation (Wilson, 1992):

$$E_a=0.35(e_s-e)(0.5+0.54u_2) \qquad \textbf{Equation 6.5}$$

where

u_2 = the wind speed in m s^{-1} at a height of 2 metres.

This equation assumes that the water temperature is the same as the air temperature. Equation 6.5 was used to predict potential evaporation in the laboratory. Since the study was laboratory based, the wind speed was assumed to be zero.

Figure 6.8 shows the cumulative actual daily evaporation for the evapopan plotted against the predicted values. The regression analysis indicates a good relationship with an R^2 of 0.999. The predictions, however are over 100% higher than the actual evaporation rates from the evapopan. Since the relationship is good, a modified equation could be used to predict evaporation from the evapopan with a reasonable degree of accuracy. The equation chosen seems to be a good empirical basis for predictions of potential evaporation, but it does not predict evaporation from the model box surface. The predicted evaporation values used the same temperature and humidity readings which were recorded during the model box experiments. If the daily evaporation rates from the evapopan are similar to the predicted potential rates, then it is suggested that evaporation

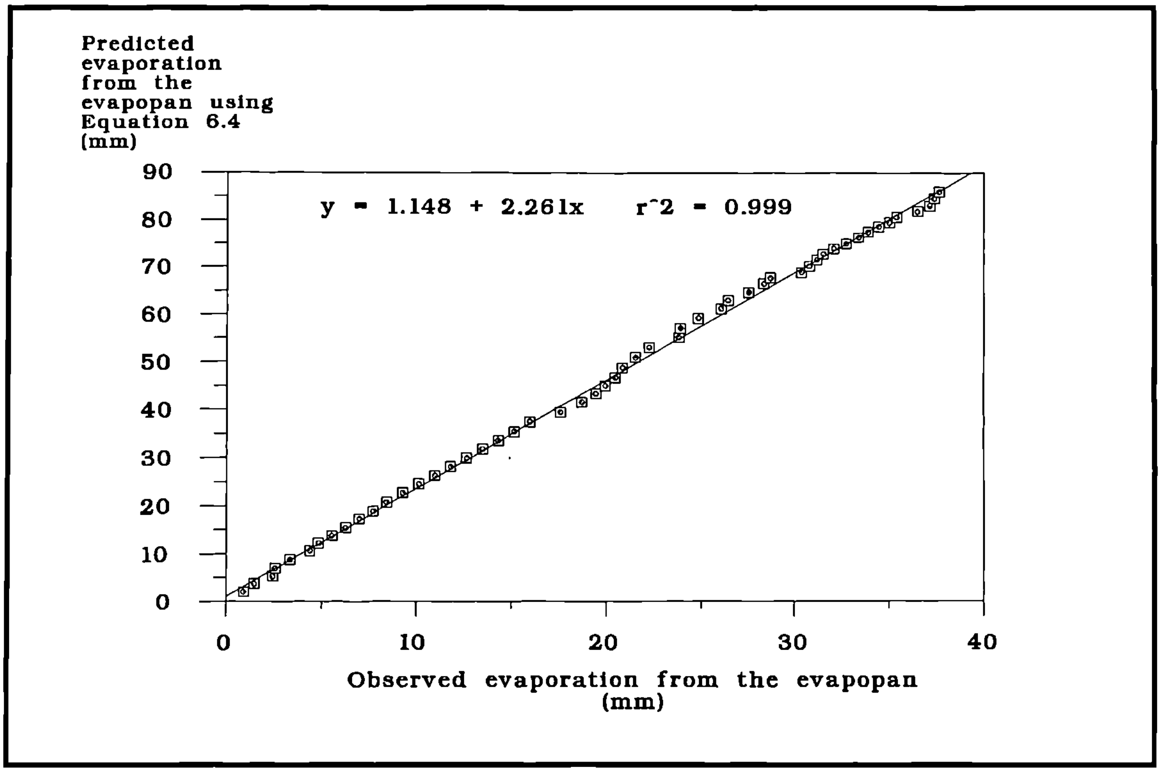
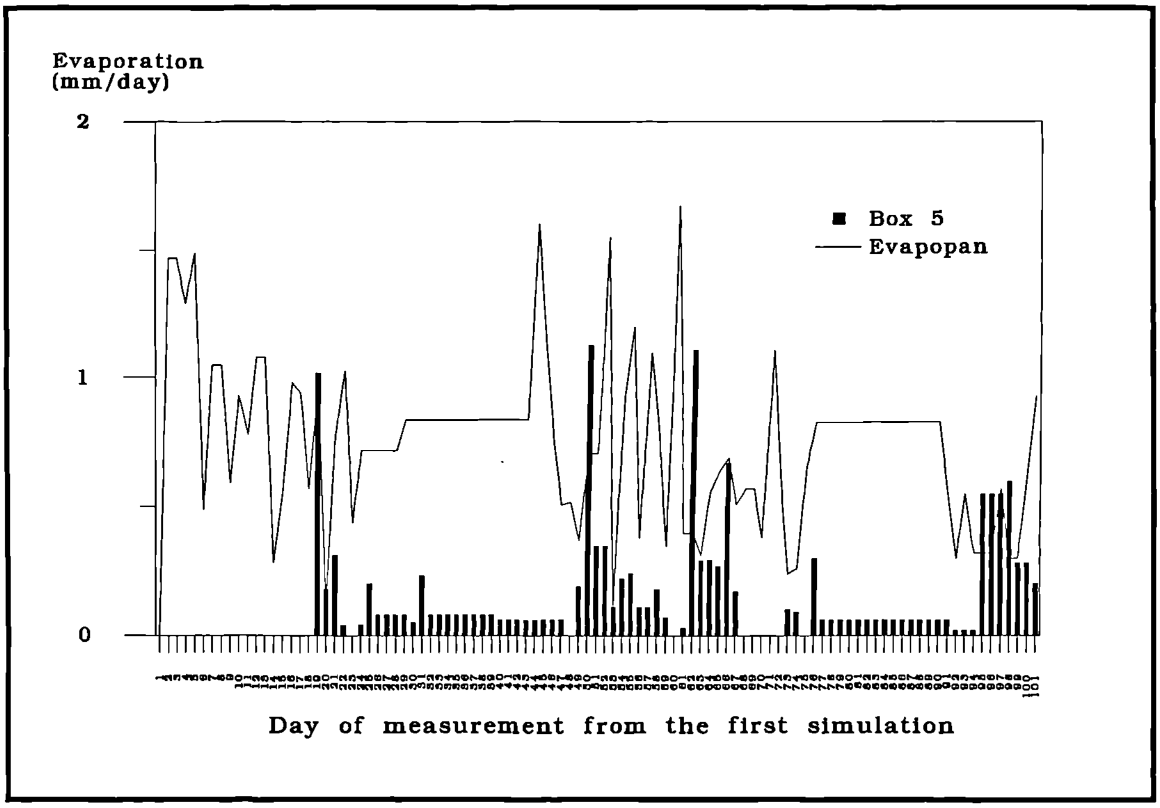


Figure 6.8 The cumulative observed daily evaporation from the evapopan plotted against the predicted evaporation using Equation 6.5.

from the evapopan must be influenced by temperature and humidity. This is suggested because the predicted rates are calculated using temperature and humidity readings.

6.3.3 A comparison of Evapopan and Box evaporation rates.

The box evaporation rates were compared with the daily evaporation rates from the evapopan. Figure 6.9 shows the daily evaporation from Box 5 and the daily evaporation from the evapopan on the same days. The evapopan losses are higher than the box evaporation rates. The box rates also decreased significantly after a rainfall event but there were significant increases in the daily evaporation rates when there were also increases in the daily evapopan rates.



<u>Figure 6.9</u> A comparison of the daily evaporation rates exhibited by Box 5 and the Evapopan.

The average daily evaporation rates were calculated for all of the boxes and are given in Table 6.2.

The average daily evaporation rates show that all boxes have a lower rate than the evapopan. Table 6.2 also shows that Box 7 has the greatest daily evaporation rate (0.22 mm day^{-1}) compared with the other boxes. This may be explained by the fact that Box 7 always retained the greatest quantity of water after a rainfall event and, consequently, had more water available for evaporation.

It is also interesting to note that the boxes containing limestone (Boxes 8, 9 and 10) had the lowest daily evaporation amounts. The boxes containing limestone usually had lower cumulative retention values when compared with the boxes containing pea gravel. Box 9 had the lowest daily evaporation rate (0.11 mm day^{-1}), which may be explained by the fact that Box 9 had the lowest cumulative retention values during the whole experiment.

<u>Table 6.2.</u> Average daily evaporation rates for all of the boxes over the inter-rainfall dry periods.

Box Number	Average daily evaporation rate (mm day^{-1})
Evapopan	0.79
1	0.16
2	0.16
3	0.16
4	0.14
5	0.14
6	0.15
7	0.22
8	0.13
9	0.11
10	0.13

It seems reasonable to suggest, therefore, that retention and water availability within the boxes influence the average long-term evaporation rates.

6.3.4 Factors influencing box evaporation.

Data from the boxes were analysed to examine the factors that influenced the evaporation process. Two factors were thought to be significant in influencing the evaporation rates. These were:

1. Experimental conditions (temperature and humidity).
2. Box components; the combination of various bedding materials and blocks influence the retention of rainfall during simulations. The retention will influence the availability of water for evaporation.

Experimental Conditions.-Potential Evaporation Calculations.

Potential daily evaporation rates calculated from Equation 6.5 are based on relative humidity and temperature readings taken in the laboratory. The cumulative potential daily evaporation calculations were compared with the actual box daily evaporation rates. Figure 6.10 illustrates the results for Box 5 which is a typical example of the patterns exhibited by the boxes. A good relationship between potential and actual cumulative rates is observed during the majority of Run 1. At point A (Figure 6.10) the cumulative daily evaporation rate for Box 5 is higher in proportion to the rest of Box 5 values (these were during the initial stages of the dry period when evaporation is expected to be higher). Figure 6.11 shows Box 5 Run 2 plotted in the same way. On analysis of fitted regression lines, the gradient is approximately 2 times higher for Run 2 than for Run 1, i.e., 0.090 for Run 2 and 0.048 for Run 1.

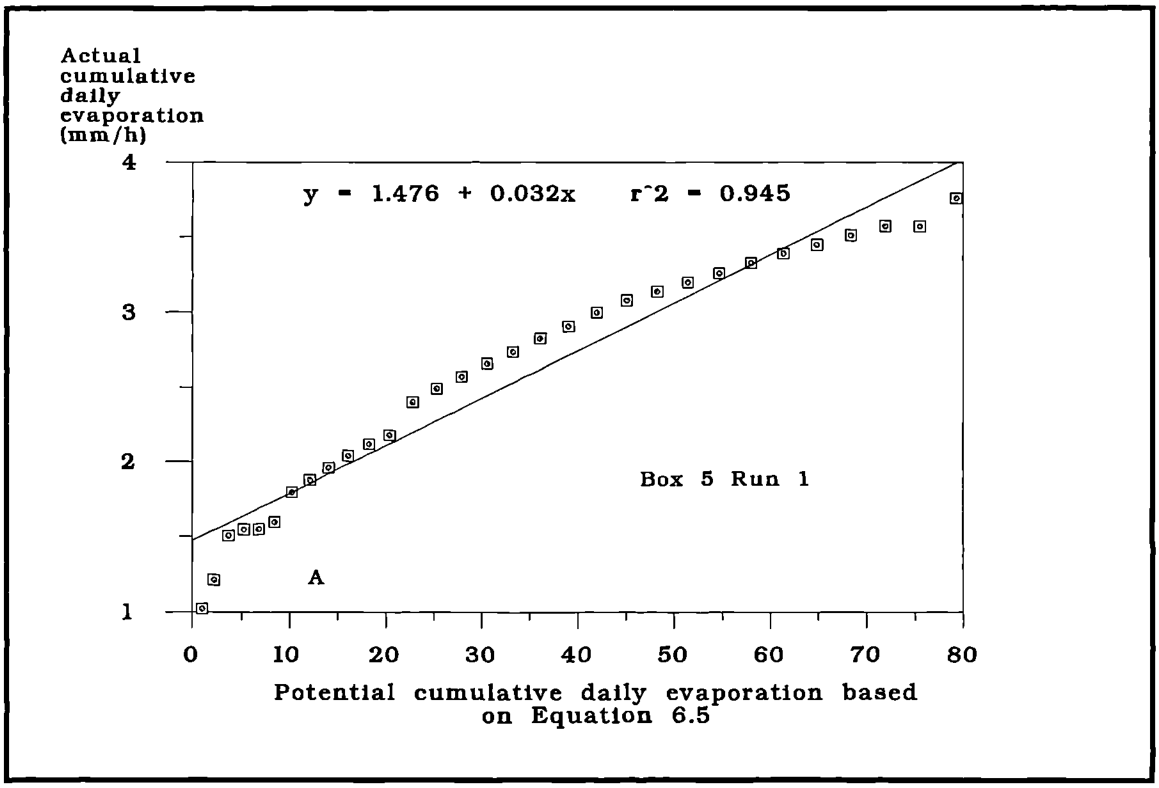


Figure 6.10 Observed cumulative evaporation from Box 5 Run 1, plotted against the predicted values using Equation 6.5.

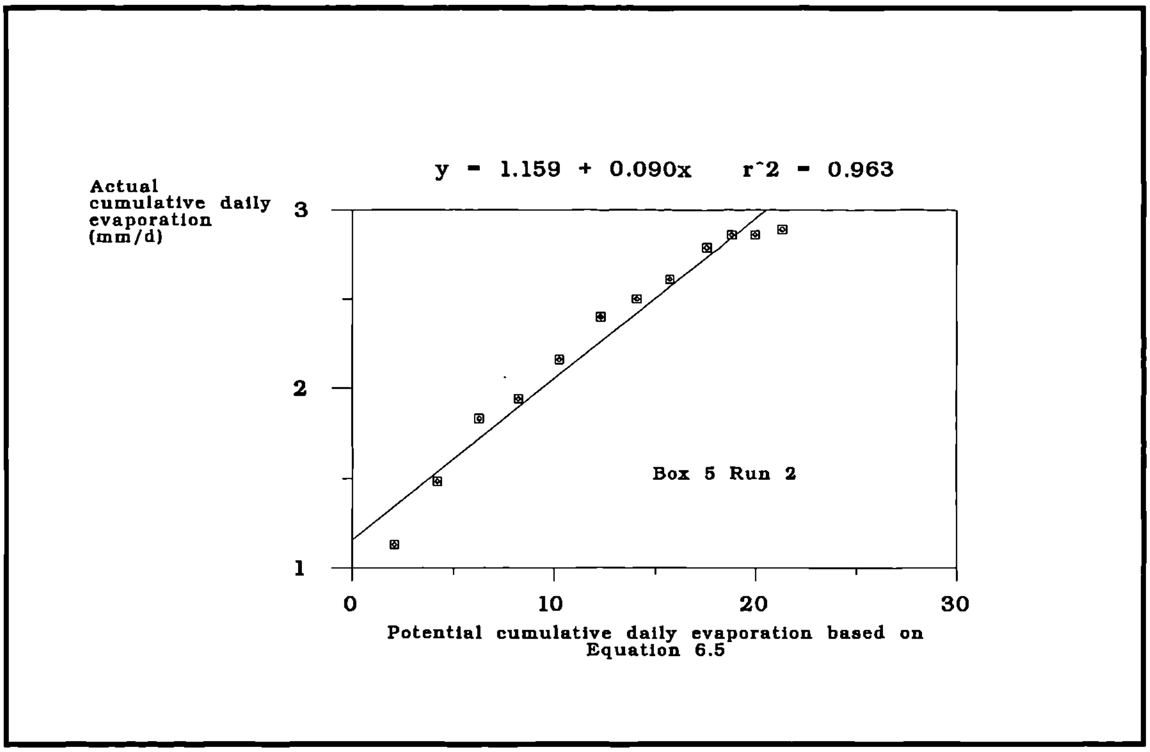


Figure 6.11 Observed cumulative evaporation for Box 5 Run 2, plotted against the predicted values using Equation 6.5.

This can be explained by the length of the dry period which was shorter for Run 2 and, therefore, was more likely to have a higher rate of evaporation over time. It is clear that evaporation from the experiment reflects a supply limitation in comparison with the potential rate.

The influence of Retention and Length of dry period.

Table 6.3 gives the total evaporation from each box after each simulation. It also gives the duration of the inter-rainfall dry period (IRP).

Table 6.3. Water lost by evaporation between each rainfall event.

Box	1	2	3	4	5	6	7	8	9	10
RUN 1 water lost (mm)	2.94	4.28	4.05	3.67	3.81	3.62	6.88	4.34	3.42	3.74
Length of IRP (h)	1.054	1.027	698	697	747	735	768	743	765	765
RUN 2 water lost (mm)	2.97	4.25	4.09	4.33	2.81	2.46	4.53	2.38	2.01	1.64
Length of IRP (h)	307	314	315	307	289	288	257	286	287	286
RUN 3 water lost (mm)	3.50	6.11	5.43	4.46	4.21	7.06	5.96	4.08	3.88	4.84
Length of IRP (h)	401	816	430	858	812	908	816	793	817	796
RUN 4 water lost (mm)	4.12	5.24	5.32	5.21	5.62	6.29	8.43	5.03	3.04	4.59
Length of IRP (h)	383	1.116	1.105	1.080	1.077	1.006	983	981	934	968

From Table 6.3. it is difficult to identify a pattern in total evaporation. This is because the length of the inter-rainfall dry periods differed for each run and for each box. If the length of inter-rainfall period is correlated with evaporation, a weak relationship can be identified (see Figure 6.12). This suggests that there are other factors which govern the total amount of evaporation from the boxes.

The post-storm retention was also identified as a factor likely to influence evaporation. To examine this control further, the maximum retention values after each rainfall event were plotted against the total evaporation following the inter-rainfall dry period. Figure 6.13 shows that there is a strong positive relationship between the maximum retention values and the total evaporation. This relationship is stronger than the evaporation / length of inter-rainfall dry period relationship. This suggests that the maximum retention amount has a significant effect on subsequent evaporation.

A multiple regression analysis was carried out on the three variables, i.e., length of dry period, volume of retention and volume of evaporation. The data were input into SPSS, a statistical package for IBM compatible Pcs. A stepwise multiple regression analysis showed that there was no significant correlation between the two independent variables of retention volume and the length of the dry period (- 0.047 correlation). The first step in the regression (where evaporation was the dependent variable) gave an R^2 value of 37.5%. The dry period had a highly significant partial correlation of 0.62. When the dry period was incorporated into the second regression step, the multiple R value was 0.79 and the R^2 was 62%.

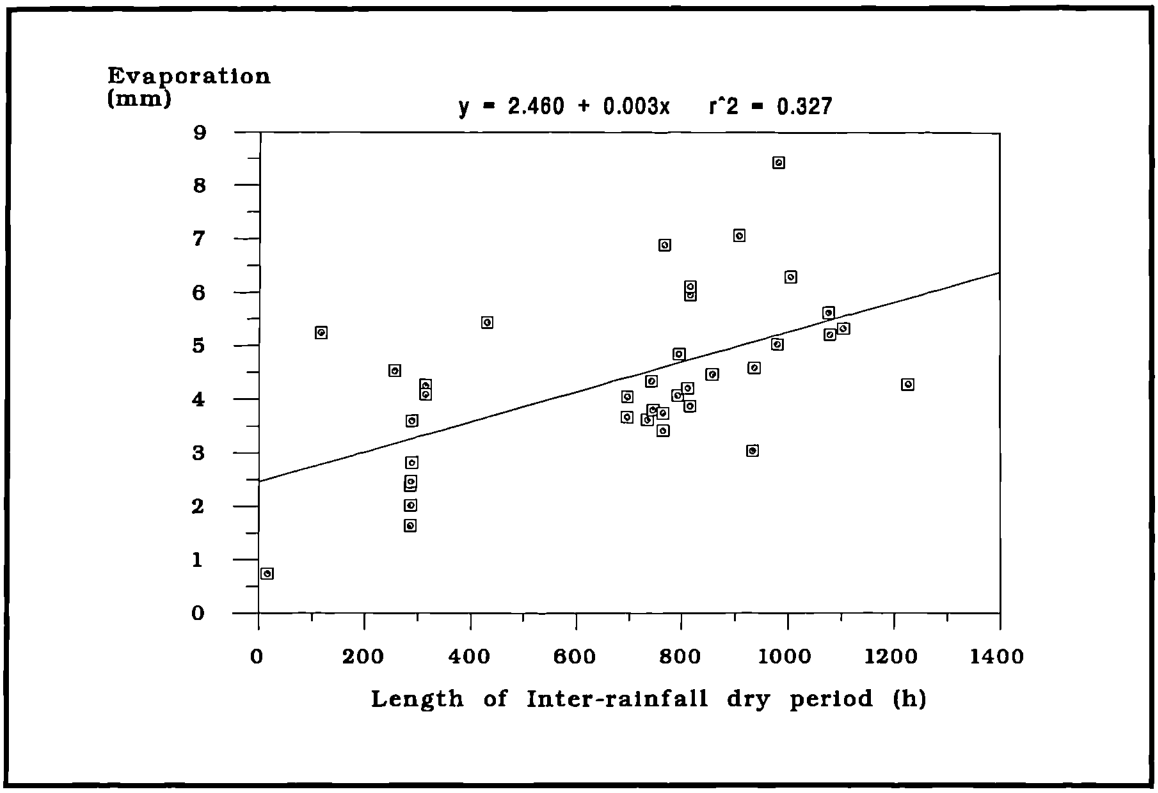


Figure 6.12 Correlation between the length of the dry period and evaporation for all boxes.

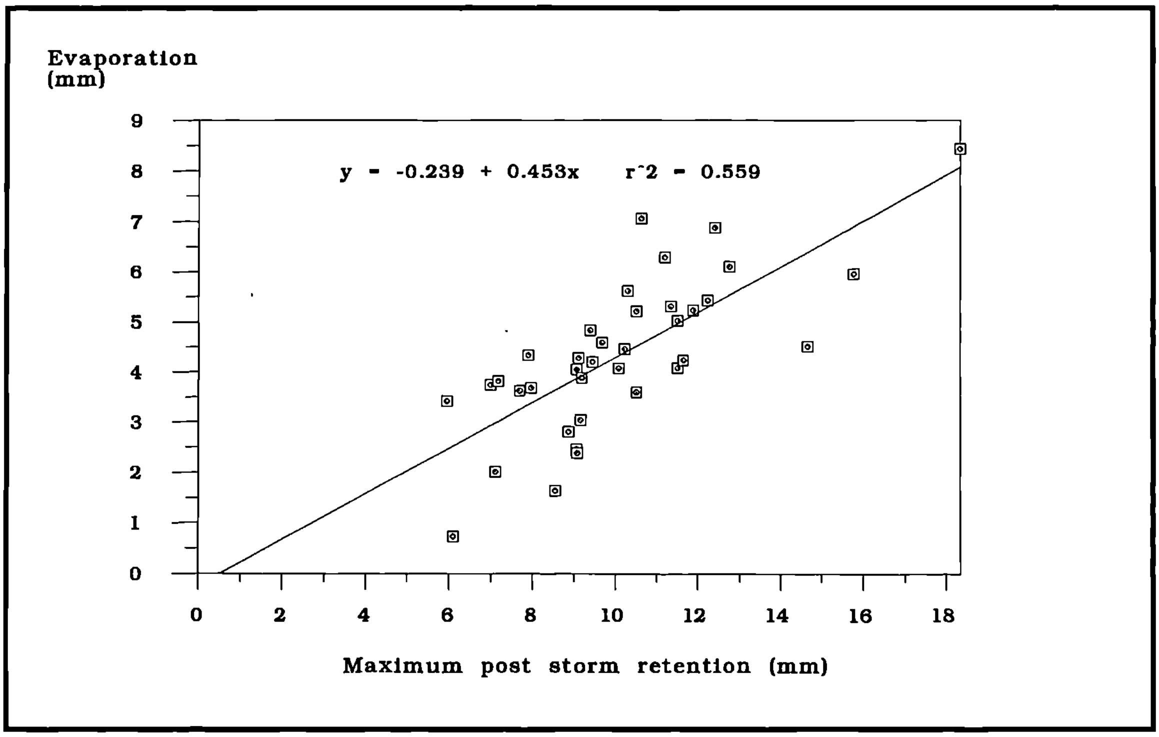


Figure 6.13 Correlation between evaporation and maximum retention.

The multiple regression analysis showed that the ß (beta) value remained reasonably stable with the addition of the second variable (being 0.64 and 0.5 for the first and second steps respectively). The multiple regression analysis explained 62% of the variance with a best fit regression curve being described by:

$$E=0.04519 + (0.27465 \times R) + (0.002445 \times IRP) \qquad \textbf{Equation 6.6}$$

where;

E = Evaporation;

R = retention;

IRP = length of dry period.

Box Components

An analysis of evaporation was also undertaken in order to provide information on the relative significance of the different structural components. A general analysis of the long-term evaporation is given, followed by an analysis of the importance of individual box components.

Analysis of Evaporation curves.

Figure 6.14 shows evaporation following the four rainfall events on Box 3. In general there were two stages identified in the evaporative process. After 50 hours the evaporation curves for the first three rainfall events begin to differ from each other and the slopes change, indicating varying rates of evaporation. Runs 2 and 3 have a higher rate of evaporation following rainfall, as compared with Runs 1 and 4. This pattern is also evident for Box 2 and, to some extent, Box 7 (after 250 hours).

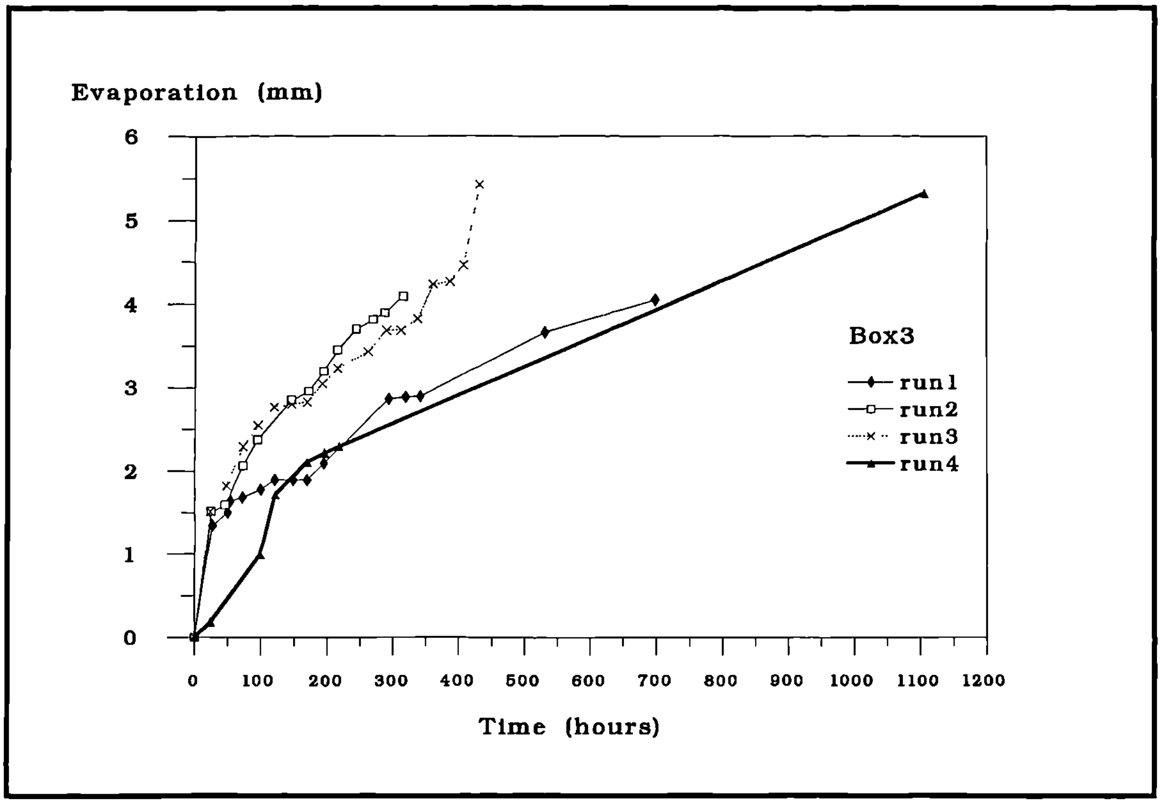


Figure 6.14 **Cumulative evaporation during each of the four runs on Box 3.**

Boxes 2,3,9 and 6 have a higher losses by evaporation during Run 3. This may also explain why Boxes 2,3 and 9 experienced a decrease in total retention after Run 4 (10 litre rainfall event), since the evaporation amount after Run 3 was higher than the absorption associated with the rainfall/block contact time during Run 4.

The rates of evaporation differed from box to box. The actual amounts of evaporation during the initial stages were similar for individual runs on each box, but the overall evaporation varied depending on the length of the inter-rainfall dry period. Boxes 1 and 7 exhibited evaporation curves that have less variation in gradient (see Figures 6.15 and 6.16) up to 200 hours. This relationship is not as strong for any of the other boxes.

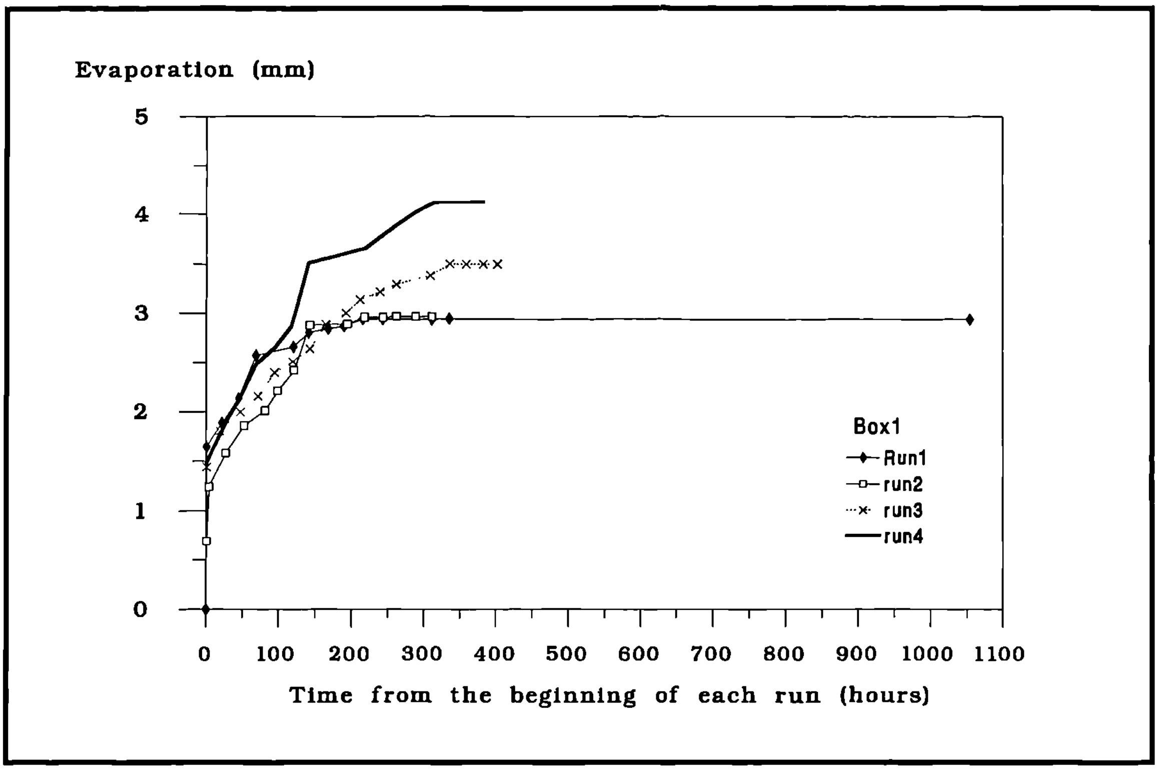


Figure 6.15 Cumulative evaporation during each of the four runs on Box 1.

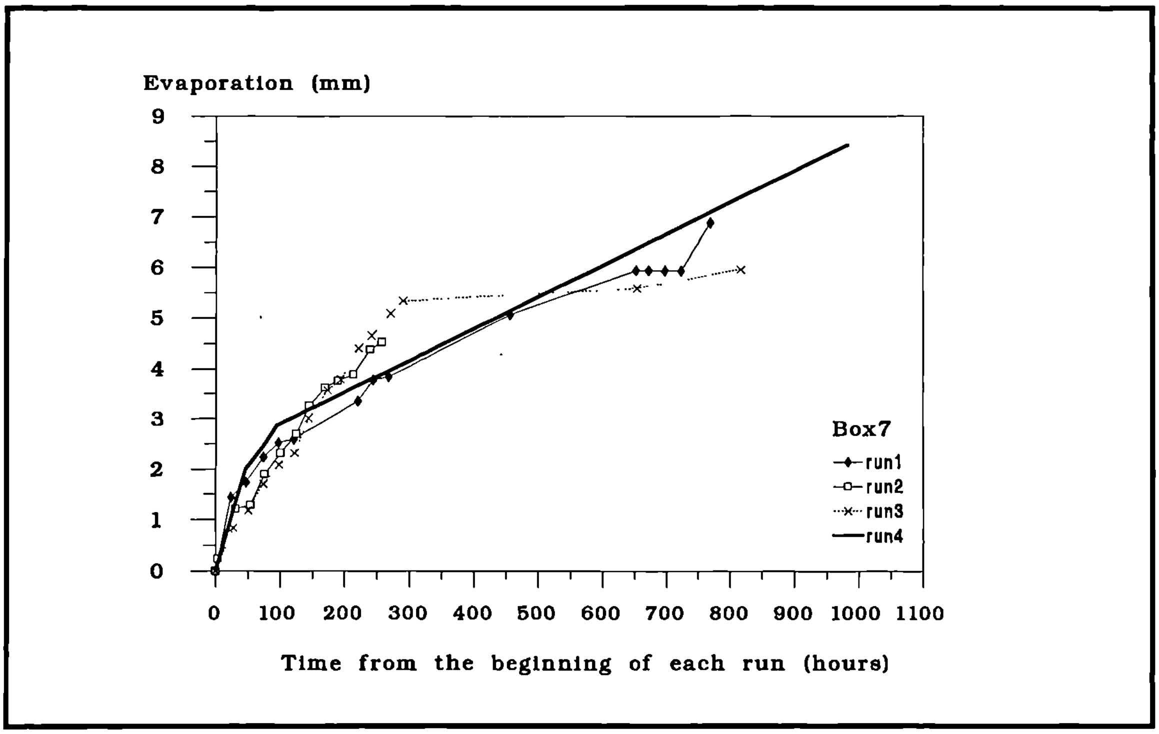


Figure 6.16 Cumulative evaporation during each of the four runs on Box 7.

Evaporation as a Percentage of Retention.

The evaporation on individual days following a rainfall event was calculated as a percentage of the total retention after each rainfall event for each box. Table 6.4. gives the water loss by evaporation as a cumulative percentage over the 15 days.

All boxes with surface blocks evaporated over 9% of the water retained after the first day following run 1. This is approximately two times higher than the block experiments in Chapter 4. It must be remembered, however, that the block experiments described in Chapter 4 had a longer contact time with water (being immersed for 1 month). The percentage values would be expected to be lower since a greater amount of water was retained in the small scale experiments. The block experiments showed an evaporation loss of 0.39 mm. The box evaporation amounts ranged from 0.98-1.03 mm, which is considerably higher, but the surface area was larger and included a 15% exposure of bedding material.

The rainfall simulation experiments were also carried out under different laboratory conditions (i.e., the block only experiments had a temperature in the laboratory ranging between 16-18 °C, whereas the box experiments had a temperature range of 17-21 °C). The presence of surface blocks in the simulated car park structure was seen to have a significant effect on evaporation rates. This is apparent if the evaporation rates from Box 1 (pea gravel only) are compared to any of the other boxes containing blocks. The rates of evaporation from Box 1 were always higher then the boxes containing surface blocks, with Box 1 losing 60% more of total retention over 15 days.

Table 6.4. Water lost by the boxes, expressed as a cumulative percentage of the total retained.

Box	RUN 1 Day 1	RUN 1 Day 5	RUN 1 Day 15	RUN 2 Day 1	RUN 2 Day 5	RUN 2 Day 15	RUN 3 Day 1	RUN 3 Day 5	RUN 3 Day 15
1	56%	87%	100%	42%	75%	100%	40%	66%	93%
2	13%	21%	30%	12%	23%	35%	11%	18%	30%
3	15%	20%	32%	13%	20%	36%	12%	22%	34%
4	22%	29%	39%	24%	30%	39%	3%	12%	26%
5	14%	18%	30%	11%	22%	29%	10%	24%	30%
6	9%	21%	27%	12%	20%	26%	13%	23%	37%
7	12%	21%	29%	7%	16%	27%	5%	13%	30%
8	17%	21%	26%	6%	14%	19%	14%	18%	23%
9	23%	30%	40%	12%	17%	24%	12%	19%	23%
10	22%	25%	36%	22%	33%	40%	8%	22%	33%

The presence of blocks therefore, reduce evaporation from the model boxes.

6.4 Summary

The analysis of the long-term hydrological performance of the car park structures is summarised below.

6.4.1 Retention

1. Cumulative retention increased as the number of rainfall events also increased.
2. During the first 50 hours specific retention is controlled by the box structural components. During the second stage of evaporation after 50 hours, the amount of water available for evaporation is a more significant influence on retention.

6.4.2 Evaporation

1. Evaporation rates from the evapopan were significantly affected by relative humidity and temperature in the laboratory.

2. Evaporation through time was estimated using Equation 6.5. Actual evaporation rates, both from the evapopan and the boxes are significantly lower then the modelled rate but follow a similar temporal pattern.
3. Evaporation from the evapopan had a higher average hourly rate than the boxes.
4. The main factors influencing evaporation were temperature / humidity conditions and box structural components. The type of bedding material influenced the hourly evaporation rates, mainly by controlling the amount of water available for evaporation. Grain size of bedding material was also shown to influence evaporation, with the smaller grain sizes providing a higher average hourly rate. Depth of bedding material also influences evaporation rates, with a greater depth of bedding material resulting in a slower transfer of water to the surface and consequently reducing water availability at the surface for evaporation.

Chapter 7 - Clogging Experiments

7.1 Introduction.

The aim of this chapter is to examine the effect that the addition of particulate material has on the long-term hydrological performance of the model car park structures. Data on particulate experiments were available from three sources;

1. field measurements from 2 sites (see Chapter 3.3.3);
2. information from experiments conducted on nine boxes to which combinations of clay and clay/peat were applied;
3. information from three boxes (which had already experienced clay/peat additions) to which graded sands were also applied (see Chapter 3.3.3).

This chapter comprises:

a) a consideration of the potential lifespan of the car park structures as a result of clogging;

b) a discussion of the observed particulate movement within the structure;

c) a discussion of the measurement of particulate concentrations within the structure, including laboratory and field data;

d) an analysis of the influence of particulate additions on the hydrological performance of the model car park structures.

Information on the clogging experiments is given in Table 7.1, which gives details of the type and rate of particulate additions.

Table 7.1. **Experimental boxes used during the clogging experiments (the type and amount of particulate additions are also shown).**

First Experiment Box	Particulate addition	Load (years)	Load (g)	Experiment 2 Graded sands addition	Load (years)	Load (g)
2	Clay	80	365	Addition	140	1873.2
3	Clay and Peat	80	365	Addition	140	1873.2
4	None			Addition	140	1873.2
5	Clay	80	365	Not used		
6	Clay and Peat	80	365	Not used		
7	None			Not used		
8	Clay	80	365	Not used		
9	Clay and Peat	80	365	Not used		
10	None			Not used		

7.2 "Lifespan" of the car park structures.

One reason for examining the clogging of the car park structure was to ascertain it's "lifespan". The "lifespan" is the estimated time after which the car park surface should be replaced, because the rate of infiltration is reduced to an unsatisfactory level. The end of the structures lifespan might be specified as when the infiltration rate was lower than 1 mm h^{-1}, being below commonly accepted design criteria (Pratt, personal communication, 1993).

After the second set of clogging experiments were completed, the hydrological performance of the car park structures was not greatly impaired. The only adverse change to the hydrological performance was periodic ponding which ceased, on average, 6 minutes after a 15 mm h^{-1}, one hour duration rainfall event (equivalent to a Return Period of approximately 2 years).

It must be stressed at this point that the clogging simulations in the laboratory involved a concentrated loading of particulate material, followed by a rainfall simulation. The intention was to examine the influence of additions and not the influence of compaction of these additions. The application of particulate material and the rainfall simulation were, therefore, not directly akin to natural conditions. Natural conditions would have a more gradual particulate loading followed by a large number of rainfall events (and a higher rainfall volume). These experiments were not designed to simulate natural particulate loading, but were employed to assess the importance of clogging.

7.2.1 Infiltration Rate and Storage Capacity.

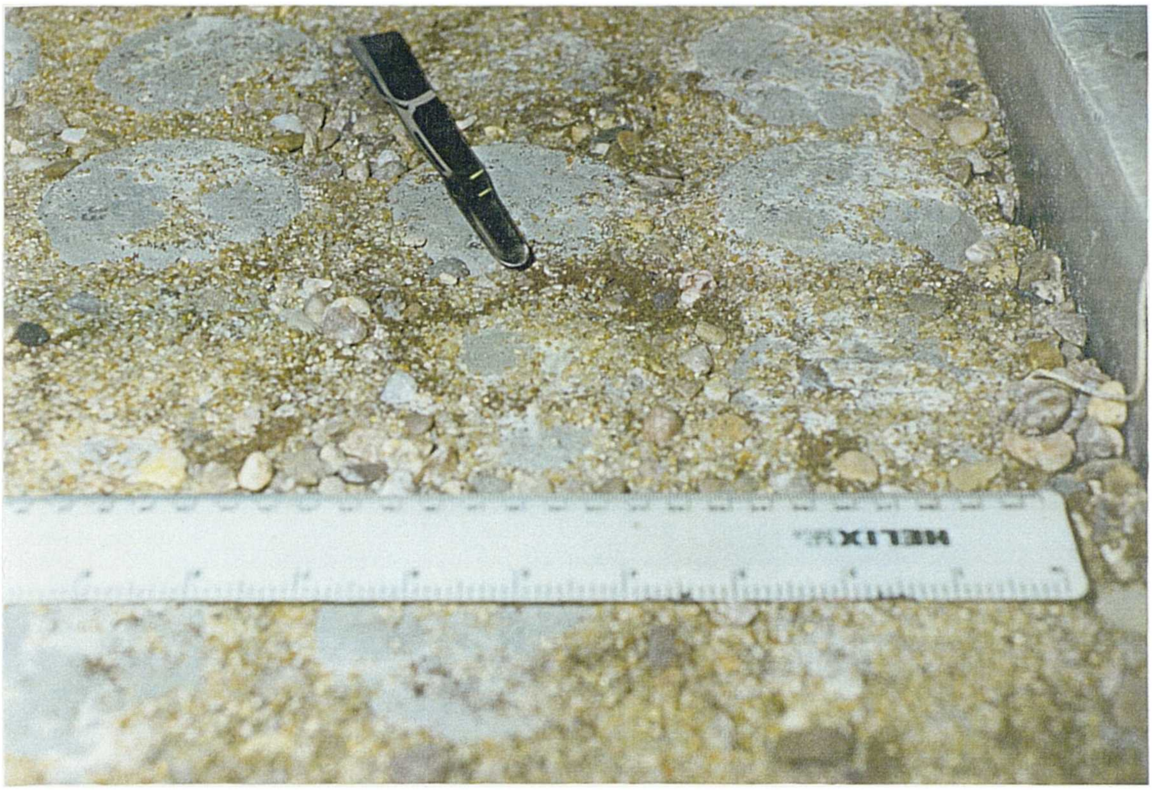
During the first set of experiments a particulate addition of 1014 g m^2 was applied, estimated to be equivalent to a load over 80 years. This particulate load was not the total load i.e. it was the equivalent loading of the organic and clay fractions only (see section 3.3.3). After particulate additions to the car park structure, drainage continued for 6 hours, an increase in drainage time by 4 hours (in comparison with experiments on clean boxes which ceased at around 2 hours). After the 80-year load had been applied, the infiltration through the structure was slower. This was caused by the "caking" of sediments at the surface, which created temporary ponding of the rainfall (see plate 7.1).

Plate 7.1. Ponding of rainfall due to particulate additions.

Field-based observations on the full-scale car park sites in Nottingham (Chapter 2.4), showed that the infiltration rates of the two car park sites were 100 mm h^{-1} (Gill Street 6 years after construction) and 146 mm h^{-1} (Clifton Campus 5 years after construction). These sites had not received maintenance since construction. The infiltration rate for Gill Street in 1987 (1 year after construction) was 1000 mm h^{-1}. This indicates an order of magnitude reduction in infiltration capacity over the six years.

On examination of the car park surface in these areas, silts were found to have accumulated in the infiltration inlets, especially the top 50 mm, which would inevitably reduce infiltration rates. Similar clogging patterns were observed during the laboratory simulations (see plates 7.2. and 7.3.). The degree of silting was observed to be greater for the experimental boxes than for the full-scale structures which was probably the result of the loads being applied over a short period of time and an overall greater amount of material added. The infiltration rate for the model car park structure, after 140 years of particulate loading (5203 g m^2) (size range 75 microns to 1.75 mm) and 80 years load of organic and clay material (1014 g m^2), was calculated as being, on average, 13.6 mm h^{-1}. Even after the particulate additions, the model structure could easily infiltrate a 7.5 mm rainfall event during one hour, even after it had experienced these heavy particulate additions. From this it may be suggested that the lifespan of the car park structure could exceed 100 years of particulate loadings without any compaction of the silts.

The void storage capacity of a structure with a 50 mm depth of bedding material is calculated, on average, to be 42% of the gravel volume (based on results from Chapter 4). From this, it is estimated that approximately 21 mm of rainfall could be stored in the voids of the bedding material alone. Observations from the laboratory and field experiments indicated that siltation occurred mainly within the top 50 mm of the infiltration inlet, with little particulate movement into the bedding material below. Therefore, the volume of voids able to retain water in the total bedding material would not be greatly reduced, and retention capabilities of the structure could still remain high. These results are not consistent with the observations by Pratt *et al.* (1988), who found that after a load simulation on a car park surface, clogging occurred from the base upwards, when large volumes of water were used to convey the sediments.



<u>Plate 7.2</u> The pattern of clogging during laboratory experiments

<u>Plate 7.3</u> Clogging of the model surface.

7.2.2 Observed Particulate Movement through the structure.

Without dismantling the experimental boxes it was difficult to quantify the depth to which particles had moved through the structure. However, observations were made on the migration of peat and clay. Two distinct observations were made;

1. the organic additions were restricted to the infiltration inlets with particles concentrated in the upper 50 mm of the structure;
2. clays were also concentrated in the infiltration inlets but some clay particles were observed to reach the base of the structure and accumulate on the geotextile.

During all rainfall simulations the peat was observed to float in the ponding water. This produced a concentration of organic material at the surface which resulted in limited incorporation of peat into the gravel in the infiltration inlets. Clay particles were removed from the structure with the drainage water. Table 7.2 gives the total loss of clay (with drainage) and the loss as a percentage of the total load applied.

Table 7.2. Loss of clay from the box structures during the particulate addition experiments.

Box Number and particle size of bedding material	Total loss of clay (g)	Loss as a percentage of total load applied
2 - 5-10 mm	86.7	23.8
3 - 5-10 mm	80.9	33.2
5 - 3-5 mm	43.3	11.9
6 - 3-5 mm	37.9	15.6
8 - 50% 5-10 mm 50% 1-3 mm	23.8	6.5
9 - 50% 5-10 mm 50% 1-3 mm	21.2	8.7

The boxes numbered in Table 7.2 all experienced particulate material additions. From the data of Table 7.2 it can be seen that the 5-10 mm grain size lost more clay during experimentation, followed by the 3-5 mm and then the 1-3/5-10 mm mixture. This suggests that the size of the bedding material has a significant influence on the migration of clays through the structure, with the smaller grain sizes providing a greater filtration of sediment which remains in the structure. The boxes with the peat/clay additions (Boxes 3, 6 and 9) lost a higher percentage of clays in comparison with the boxes experiencing clay-only additions (Boxes 2, 5 and 8) which may be due to more efficient particle cohesion between clays then clay and peat.

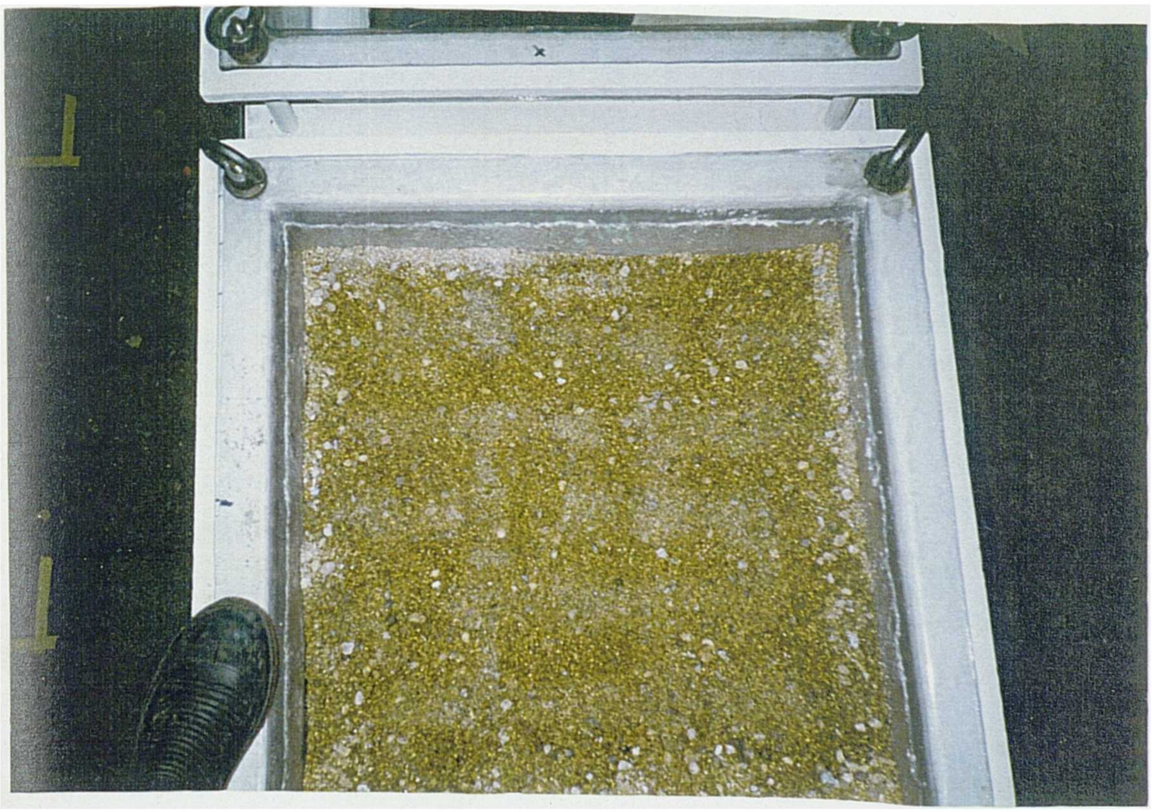


Plate 7.4. **Migration pathways of clay particles.**

When the boxes were dismantled, the pathways of clay migration were distinctly visible (see Plate 7.4). The visible white patches of clay were located directly under the infiltration inlets, showing that the migration path of the clays was concentrated in the areas immediately below the point of entry of the percolating waters. The pattern extended down to the geotextile at the base of the structure where the clay collected and moved laterally.

The graded sand, which was added during the second set of experiments, was also retained in the infiltration inlets, again with a high concentration in the top 50 mm of the inlet. A small proportion of the sand was observed to reach the bedding material at the base of the infiltration inlet.

7.3 A comparison of Laboratory and Field Observations.

The field observations were made at two sites in Nottingham. The first site was Gill Street in the centre of Nottingham and the second was at the Clifton Campus at Nottingham Trent University. Gill Street (see Plate 7.5) field site was a car park used by the public in a busy shopping area of Nottingham. The bedding material used in construction had a grain size ranging from 2-6 mm. The infiltration inlets surrounding one of the surface blocks were carefully excavated. Each infiltration inlet was divided into two samples, the top 50 mm being sample 1 and the 50 mm below that being sample 2. In total, 6 infiltration inlets were excavated. It was observed that the migration of sediment through the surface of the structure was concentrated around the infiltration inlets.

Plate 7.5. Gill Street field site - shopping area, Nottingham.

Plate 7.6. Gravel under the surface block.

From Plate 7.6 it was clear that there was no lateral movement of sediment to the area directly below the surface block. The gravel below the block was, by contrast, very clean. The observed migration was similar to that evidenced by the migration of clays during laboratory analysis.

A similar procedure was carried out at the Clifton Campus site (see Plate 7.7). The bedding material ranged between 1.18 and 10 mm. After excavation, it was again noted that the migration of particulate material through the surface of the structure was concentrated in the infiltration inlets. The clean gravel directly below the surface block was also similar to that found in Gill Street (see Plate 7.8). It must be stressed at this point that the analysis which follows is based on information gained from the infiltration inlet and not the bedding material below the surface blocks.

The excavated gravels from both sites were dried and sieved into size fractions. Table 7.3 gives the size fractions in the samples as a percentage of the total sample. The size fractions below 1.18 mm are assumed to be the particulate loading onto the surface since the gravels used during construction of the surfaces all had a grain size greater than 1.18 mm.

For Gill Street, 8.37% of the material from the infiltration inlet weighed was of a size fraction less than 1.18 mm. The value for Clifton Campus was 3.02%. The difference may be explained by the age of the structure and the initial particle size distribution.

Plate 7.7. **Clifton Campus, Nottingham.**

Plate 7.8. **Gravel located below surface block.**

Gill Street was constructed about a year before the Clifton Campus producing a difference in cumulative particulate loadings per year; and the grain size of the bedding material at Gill street was smaller, providing greater infiltration possibilities.

The distribution of the particulate material through the structure showed a concentration of material in the first 50 mm of the infiltration inlet. The samples from the field sites were examined to quantify this observation. The concentration in the first (0-50 mm) and second (50-100 mm) samples were calculated as a percentage of the size fraction below 1.18 mm (see Table 7.4). Table 7.4 shows that the percentage of particulate material in the first sample was significantly higher in both cases (see Plate 7.9). The results from Gill Street indicate that the older the construction, and the smaller the grain size of bedding material, the greater the concentration of particulate material in the upper 50 mm.

<u>Table 7.3.</u> The weight of each size fraction was calculated as a percentage of the total infiltration inlet sample weight.

Size Fraction	**>1.18 - < 5 mm**	**<1.18 mm >600**	**<600 >300**	**<300 >150**	**<150 >75**	**<75**
Gill Street	91.64%	1.98%	1.79%	1.94%	1.56%	1.09%
Clifton Campus	96.97%	0.80%	0.96%	0.64%	0.30%	0.33%

<u>Table 7.4.</u> The concentration of material (< 1.18 mm) in the 0 - 50 mm and 50 - 100 mm samples as a percentage of the total material less than 1.18 mm.

Site	**Percentage of the size fraction <1.18 mm contained in the top 50 mm of the infiltration inlet**	**Percentage of the size fraction <1.18 mm contained at a depth 50-100 mm in the infiltration inlet**
Gill Street	83.82%	16.18%
Clifton Campus	68.53%	31.47%

Plate 7.9 **Samples taken from the infiltration inlet.**

The degree of clogging was also estimated as a percentage of the total volume of voids in the infiltration inlet. Table 7.5 gives the results for the field sites and a selection of the experimental boxes as well as the average infiltration rate.

The field site results indicated that the older the structure, the higher the percentage of void fill and the lower the infiltration rate. The box studies also show a higher percentage of void fill which would be expected, since the loadings on the boxes were higher than the particulate additions at the field sites. The boxes also had a significantly lower infiltration rate.

Table 7.5. Infiltration rates measured after particulate additions.

Site (average value)	Infiltration rate (mm h^{-1})	Volume of particulate material as a percentage of the total volume of voids in the infiltration inlet.
Clifton Campus	146.0	9.23%
Gill Street	100.0	15.25%
Boxes with clay/sand additions	14.4	21.69%
Boxes with sand only additions	15.0	17.93%
Boxes with Clay/peat/sand additions	13.6	32.50%

A small percentage increase of void filling (2-3%) in the infiltration inlet seems to have a dramatic impact on the rate of infiltration. The storage potential of the bedding material below the surface blocks should remain high, but the infiltration rate will be influenced by the degree of void filling in the top 50 mm of the infiltration inlet.

7.4 Laboratory Experiments.

7.4.1 Influence of clogging on box retention.

5-10 mm bedding material grain size boxes.

All of the boxes in Table 7.6 had a similar weight and depth of 5-10 mm pea gravel. The clay and clay/peat additions were of the same quantity. Box 4 had no particulate additions and was used as a control box. All boxes contained surface blocks. The average cumulative retention over 13 rainfall events shows that the presence of the particulate material increased the retention by around 0.9 mm (for the 80 year load). If the percentage difference from the control box is calculated, there is a 16% higher retention in Box 2 and 18% higher retention in Box 3.

Table 7.6. Retention after rainfall events by the boxes containing pea gravel with a grain size of 5-10 mm.

Box	Particle additions	Average retention after each rainfall event (mm)	Average cumulative retention over 13 rainfall events (mm)
2	Clay	2.17	6.53
3	Clay and Peat	2.45	6.63
4	None	1.65	5.63

Table 7.7. Retention after rainfall simulations by the boxes containing pea gravel with a grain size 3-5 mm.

Box	Particle additions	Average retention after each rainfall event (mm).	Average cumulative retention over 13 rainfall events (mm).
5	Clay	2.59	11.86
6	Clay and peat	2.74	11.35
7	None	2.14	10.86

Table 7.8. Retention after rainfall simulations by the boxes containing a mixture of pea gravel with varying grain sizes.

Box	Particle additions	Average retention after each rainfall event (mm).	Average cumulative retention over 13 rainfall events (mm).
8	Clay	2.25	11.84
9	Clay and peat	2.91	13.28
10	None	2.00	11.81

The inclusion of peat in the particle additions caused a marginal increase in retention (on average 0.1 mm). This may be due to the absorption of water by the peat fraction.

3-5 mm bedding material grain size boxes.

The boxes in Table 7.7 all had a similar weight and depth of 3-5 mm pea gravel as well as surface blocks. In comparison with the boxes containing 5-10 mm gravel, the boxes with 3-5 mm gravel, had a greater average retention, both after each rainfall event and as an average cumulative retention over the 13 rainfall events.

In comparison with the boxes containing 5-10 mm gravel, the boxes with 3-5 mm gravel had a greater average retention, both after each rainfall event and as an average cumulative retention over the 13 rainfall events. This suggests a pattern similar to the results given in Chapter 6, in that the smaller grain sizes tend to retain more rainfall. Again Box 7, which had no particulate additions, had a lower retention value, 0.49 mm on average less than the other boxes which experienced additions. Box 5 retained 9% more and Box 6 retained 5% more than the control Box 7. These results differ to the results from Table 7.6 where the clay/peat additions had a greater retention then the two other boxes. This suggests that grain size is a more influencing factor in determining the retention in the 3 - 5 mm gravels.

Box 6, on average, retained the most water after each rainfall simulation (0.15 mm more than Box 5 and 0.6 mm more than Box 7). The boxes containing 5-10 mm pea gravel as bedding material showed that the clay/peat particle additions retained more water after a rainfall simulation, both for the single events and for the average cumulative retention.

However, the average cumulative retention values for the 3-5 mm bedding material experiencing clay/peat additions had a lower retention than the clay additions alone. Since cumulative retention over the storms was influenced by evaporation during the inter-rainfall dry periods, evaporation had to be studied before this could be fully explained. The average retention after each rainfall simulation showed that Box 6 had the highest average retention followed by Box 5 and then Box 7. This suggested that the presence of organic matter has an influence on the retention.

50% 5-10 mm and 50% 1-3 mm bed material grain size boxes.

The incorporation of a smaller grain size material into Boxes 8, 9 and 10 was expected to increase the average retention values (based on the results from Chapter 6). Box 9 had 12.4% more and Box 8 had 0.2% more retention than the control Box 10.

The average cumulative retention values over the 13 rainfall simulations on boxes experiencing similar additions were: 1.93 mm higher for Box 9 than Box 6 (clay/peat additions); 0.95 mm higher for Box 10 then for Box 7 (no additions); but Box 8 was 0.02 mm lower than Box 5. As with the other Boxes, the presence of particulate material seems to increase both the average retention after each rainfall event and the average cumulative retention over the 13 rainfall events.

7.4.2 Evaporation

Clay/peat particulate addition experiments.

Each of the three types of bedding materials were set up in three boxes: one box which experienced no particulate additions; one box to see whether clay particulate additions influenced evaporation; and one box to see whether a combination of clay and peat additions increased or decreased evaporation from the surface. Since these experiments were carried out at a different time of the year than the clean box experiments, the evaporation data from Chapter 6 could not be used for direct comparison. A box was selected as a control box, with no particle additions but experiencing the same rainfall simulations.

The analysis of retention showed that the presence of particulate material increased the retention of rainfall. This should also influence long-term evaporation by increasing the amount of water available for evaporation. The evaporation analysis in Chapter 6 suggested that there were two stages in the evaporation process (stage I was up to 50 hours and stage II was after 50 hours). The results from Chapter 6 also suggested that the influence of box components on evaporation was more dominant during stage I. The first stage of evaporation was chosen for comparison since:

1. the inter-rainfall periods were not, in general, greater than 72 hours and it was therefore not possible to fully analyse stage II;
2. box components had a more significant influence during stage I in comparison to stage II; and
3. the presence of particulate material changed the structure of the box.

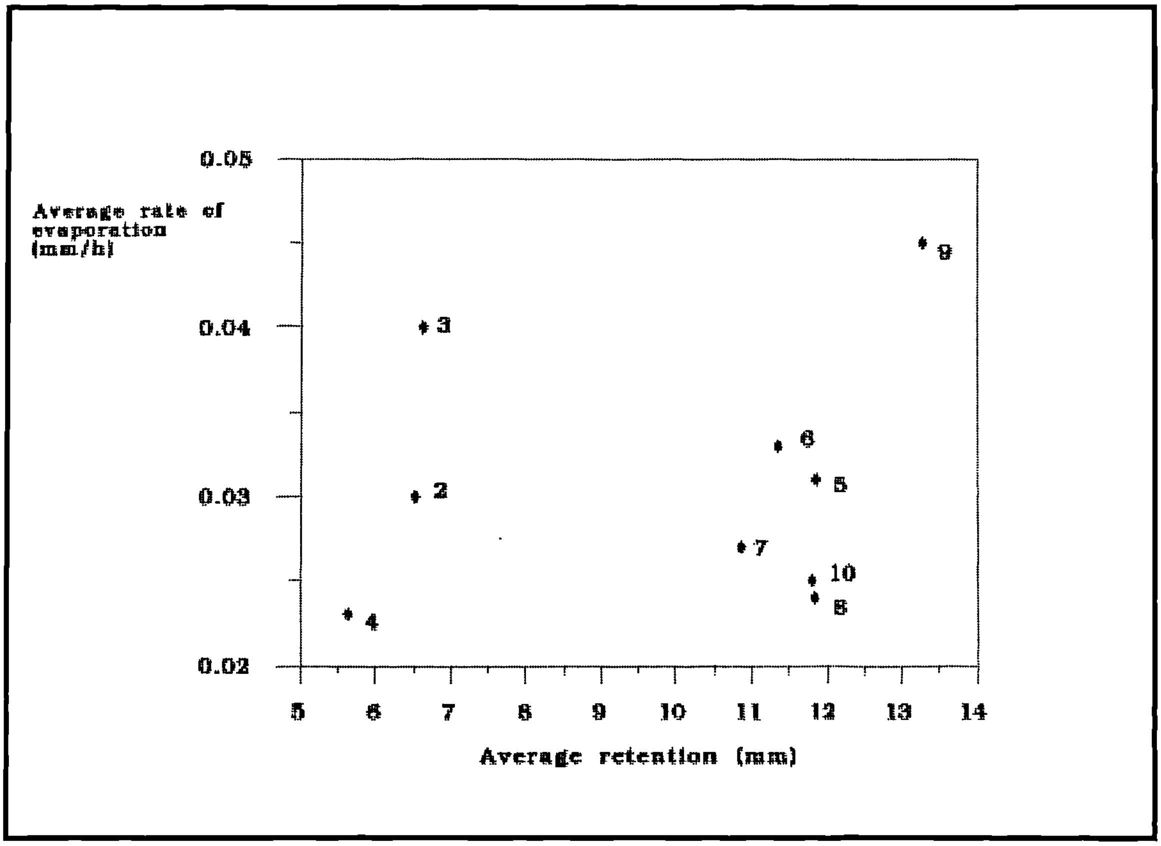
The evaporation after approximately 50 hours following a rainfall simulation was divided by the time interval and an average was calculated for each box. Table 7.9 gives the results as well as the average hourly rate over all of the simulations. Each box experienced 13 simulations during the whole experiment.

To summarise the results in Table 7.9, the highest hourly evaporation rates during the first stage of evaporation are shown by all of the boxes containing the clay/peat additions. All three boxes (Boxes 9, 3, and 6) have the three highest rates (0.045, 0.040, and 0.033 mm h^{-1} respectively). The presence of clay/peat seems to have a more significant effect than the initial grain size distribution. This leads to two conclusions; first, the presence of peat in the boxes increases the rate of evaporation and, secondly, the presence of these additions have a more important influence on evaporation than do the box components. This second fact is further validated by the second highest rates being shown by the boxes that experienced clay additions, with the exception of Box 8, which was marginally lower than Box 10 (receiving no additions). These results suggest that the condition of the surface of the car park structure is the most critical control on evaporation rates.

Table 7.9. The average hourly evaporation rates during the first stage of evaporation (up to 50 hour).

Box Number	Type of addition	Average hourly evaporation rate up to 50 hours (mm h^{-1})	Average hourly evaporation rate over the whole experiment (mm h^{-1})
2	Clay	0.030	0.035
3	Clay/Peat	0.040	0.036
4	None	0.023	0.025
5	Clay	0.031	0.034
6	Clay/Peat	0.033	0.035
7	None	0.027	0.025
8	Clay	0.024	0.024
9	Clay/Peat	0.045	0.035
10	None	0.025	0.020

The average cumulative retention after each rainfall simulation was compared with the average hourly evaporation rates up to 50 hours (see Figure 7.1). It was noticed that the box which had the highest retention per event (Box 9) also had the highest average hourly evaporation rate up to 50 hours. The box which retained the least (Box 4) also had the lowest average hourly rate up to 50 hours. Although the two extreme end values are consistent with expectations, the rest of the boxes did not show such a strong relationship between retention and the hourly evaporation rate. However, this does seem to suggest that retention influences the rate of evaporation, thus confirming previous findings (Chapter 6).



<u>Figure 7.1</u> **The average hourly rate of evaporation (mm h^{-1}) plotted against the average retention (mm). The numbers refer to the box number.**

The Graded Sand Particulate Addition Experiment 2.

The second set of particulate addition experiments were carried out on Boxes 2, 3 and 4. The particulate additions were composed of graded sands. In total the equivalent of 140 years load of each fraction was applied to each box. The inter-rainfall dry periods were shorter during this experiment (approximately 24 hours between each rainfall simulation) and therefore the average hourly rates up to 24 hours after rainfall were used for comparison. Table 7.10 gives the results.

Boxes 2 and 3 had already experienced the particulate loadings during the clay/peat particulate addition experiments. Again it can be seen that the box which experienced peat addition (Box 3) had the highest hourly rate, followed by the box containing clay.

Box 4 experienced no particulate additions during the first set of experiments and had an hourly rate of evaporation (up to 24 hours) then of 0.030 mm h^{-1}. After the sand was applied this hourly rate increased to 0.034 mm h^{-1}. This suggests that the addition of particulate material to the box structure increases the hourly rate of evaporation during the initial stages of the inter-rainfall dry period.

Table 7.10. The average hourly evaporation rates exhibited by the boxes during the second particulate experiment.

Box Number	Average hourly evaporation rate up to 24 hours following a rainfall simulation (mm h^{-1})
2	0.037
3	0.038
4	0.034

7.5. Summary of Chapter 7 and conclusions.

The presence of particulate material increases the evaporation rates during stage I (0-50 hours following rainfall). This confirms the observations made by Wind (1961), who showed that if clays overlie sand, the hydraulic conditions created would favour a higher rate of capillary movement through the material to the surface by comparison with sand overlying clays. There is also a tendency for boxes containing peat additions to have a higher evaporation rate. If particulate additions also increase the retention of rainfall, it seems reasonable to suggest that particulate additions to the surface of the car park structure will increase the overall evaporation rates from the structure. If the intention is to store a larger proportion of rainfall and induce evaporative losses at a higher rate, then the hydrological performance of the car park surface will be favourably enhanced after clogging has occurred despite the decrease in infiltration.

Chapter 8 - Modelling the Hydrological Performance of the car park surface.

Modelling and Models

"A model must be simple enough for manipulation and understanding by it's users, representative enough in the total range of the implications it may have, yet complex enough to represent accurately the system under study." (Chorafas, 1965)

8.1 Introduction

This chapter describes an empirical model which has been developed from the research findings which were presented in Chapters 4 to 7, and assesses it's validity as a tool for predicting the hydrological performance of the various car park structures. Although it is not the aim of this chapter to fully optimise the model some attempts have been made to improve it's performance using various empirical equations developed in previous chapters. Hydrological simulations on the model car park structures were discussed in the previous chapters and the results from these experiments were used to formulate the model structure and provide the data used in the simple empirical equations developed. The model was written in Qbasic.

There are many types of models which might be developed but it is not the aim of this chapter to discuss the myriad of modelling strategies available. Models can generally be divided into two groups ;

1) Deterministic models which determine, through theory an output from a given input. They simulate a system by using known parameters based on a theoretical structure (Overton and Meadows, 1976), i.e. they are process response models.

2) Stochastic models involve an element of time. Hydrological variables are measured and the probability of an outcome is produced (Shaw, 1994).

The model developed in this research chapter is a deterministic process response model (Section 8.2). The model is an empirically or physically based model which aims to describe realistically the component processes of the hydrological performance of a model car park structure.

Component models aim to describe hydrological processes using exact governing equations which have been rigorously tested. There is one disadvantage of these models in that they treat each process as an individual component and then try to link the components. This may produce problems in operational use since it simplifies to a great extent the complexities that exist in the examination of hydrological processes.

Examples of similar approaches to modelling hydrological processes include the MIT catchment stream model (Bravo *et al.*, 1970), the SWMM model (Metcalf *et al.*, 1971; Diniz, 1978), the SHE model (Jonch-Clausen, 1979) and the TOPMODEL (Beven *et al.*, 1984). The development of these models have been aided by computer systems which allow complex interactions to be analysed simultaneously using small time steps and run over long time periods.

With the introduction of computer systems, a large number of complex interactions can be analyzed simultaneously using small time steps and run over long time periods (years). For example the SHE model (Systéme Hydrologique Européen) (Jonch-Clausen, 1979) examined a number of hydrological variables over a catchment, using measurements from 2000 grid points on the horizontal axis and 30 vertical points. The amount of data produced was large but the potential applicability has been good.

TOPMODEL is designed to calculate runoff from hill-slopes in ungauged catchments which is then routed downstream to give a catchment discharge (Beven *et al.*, 1984). It considers evaporation, precipitation, interception storage, infiltration storage, saturated zone storage, contributing area, quick return flow delay, to estimate channel flow.

The Stormwater Management Model (SWMM)(Metcalf *et al.*, 1971; Diniz, 1978) produced by the EPA, is another example of a complex component model with multiple variables. It has five interacting sections which measure the rainfall and catchment characteristics to determine the quantity and quality of runoff. This model also incorporates the possibility of using combined sewer systems and can assess the impact of water quality and quantity on receiving waters.

The concept of producing a predictive deterministic hydrological component model is not new, but the model outlined in this chapter is unique. This model predicts, retention discharge and evaporation from a car park surface over an extended time period. It also allows hydrological conditions (including antecedent conditions) to be predicted over consecutive rainfall events. The model can also predict the hydrological response from five differing bedding materials.

8.2 Choice of model

The model developed in this research programme was of a process-response type. It is a deterministic model, since a determined output is produced from a stated set of input values. The input variables in the model are surface characteristics and rainfall. The modelled outputs from the car park structure are evaporation and drainage. Retention by the structure was also modelled.

The choice of model developed was determined by three factors: first, the processes under investigation, secondly, factors influencing these processes and thirdly, and the available data. The variables investigated in this research project were:

1) Retention;
2) Discharge;
3) Evaporation.

Factors influencing these hydrological characteristics, were identified during the research (Chapter 4 to 6) and included:

1) Rainfall depth and duration;
2) Variations in the structural components of the car park;
3) Differing antecedent conditions.

During the hydrological experiments (Chapter 4 to 7) the significance of these factors were controlled and isolated and quantitative information was derived on the retention and evaporation performance of the two structural components namely;

1) the surface blocks;

2) the bedding material (Chapters 4 to 6).

Various combinations of these two components in the model box experiments showed that both of them had a significant influence on the response of the structure (evaporation and drainage) to a rainfall input.

8.3 Model predictions.

The model was designed to predict the following variables:

1) maximum retention for a known volume of bedding material;

2) block retention over time;

3) total discharge from the structure under given rainfall and surface component characteristics;

4) total evaporation from the bedding material for dry periods;

5) total evaporation from the block surface for dry periods;

6) total retention in the structure;

7) total evaporation from the structure;

8) retention after a known inter-rainfall dry period;

9) retention prior to a rainfall simulation on a structure that had experienced previous rainfall.

8.4 Data Input Requirements.

To predict the variables listed above, input data were required. These input data were:

1) Rainfall duration (hours, minutes) and depth (mm) for each rainfall event;

2) Surface area of the structure (m^2);

3) Depth of bedding material (mm);

4) Grain size and type of bedding material;

5) Length of dry period (hours, minutes);

6) Number of rainfall events.

All these data were requested by the model prior to calculation.

8.5 Model Assumptions.

The structure of the model was shaped by a number of assumptions which were based on the experimental findings discussed in Chapters 4-6. The model calculated retention and evaporation by a car park which contains both bedding material and surface blocks. It was assumed in the calculations that the surface blocks covered 85% of the surface area and the other 15% of the surface area was open bedding material. The section below discusses how retention and evaporation by the bedding material and surface blocks were calculated and reference is made to the sources of data on which these assumptions were based.

Bedding material retention.

A comparison was made between small-scale bedding material retention experiments and model box experiments (containing only pea gravel 1 - 10 mm) in Chapter 4 (section 4.6.1). The small-scale experiments showed that the bedding material had a maximum specific retention which was not affected by the contact time with water. If information on bedding material specific retention (Table 4.2) was incorporated into Equation 4.6, the retention of water by a known volume of gravel could be calculated. When the prediction of retention, based on the small scale results, was compared with model car park structures containing only bedding material, a difference of only 1% was observed.

Since the percentage difference was small, it was decided that the computer model could calculate bedding material retention using the data of Table 4.2 and Equation 4.6. The model assumed that each bedding material could only retain a maximum amount, depending on the grain size and type of material in the sub-matrix. The maximum was derived from the experiments discussed in Chapter 4.4.1.

If the rainfall applied to the structure was less than the maximum specific retention of a bedding material, then the retention was calculated as 15% of the rainfall. This was based on the fact that the bedding material covered only 15% of the surface area.

Bedding material evaporation.

Chapter 4 discussed evaporation losses from the bedding material and compared the response of the small-scale experiments with pea gravel (1-10 mm) to a model box containing no blocks and the same bedding material (Chapter 4.6.2). A 21% under-estimation for the small scale experiment was calculated after the first stage of evaporation (Stage I up to 50 hours of the inter-rainfall dry period). This difference was attributed to errors associated with scale effects and may be regarded as a source of error if these small-scale experimental data were used to predict evaporation from a full-scale structure. However, only one bedding material type and size range were examined. At this stage it was decided that the small-scale results from Chapter 4.4 could be used as an estimate in the model although it was appreciated that evaporation rates from the bedding material would need to be optimised at a later stage in model development. The model assumed that evaporation from the bedding material took place from only 15% of the surface area of the structure since the blocks covered 85% of the surface area.

Surface block retention.

The retention of water by dry concrete surface blocks could be calculated using Equation 4.4, but this equation tended to under-estimate retention by around 16% when compared to the retention by a model box containing only blocks (Chapter 4.5.3, Table 4.10). Equation 4.4 did not incorporate the effect of pre-storm retention which was identified as a source of potential error in Chapter 5.4.

Variations in methods used to predict block retention were discussed in Chapter 5.4, where it was concluded that a measure of pre-storm retention should be incorporated into Equation 4.4. This method used the storm contact time plus the pre-storm retention (calculated as a time equivalent using the inverse of (t) in Equation 4.4 log(t)) to estimate retention after more than one rainfall event. If more than one rainfall event was to be modelled, the first rainfall event used Equation 4.4 (assuming no pre-storm retention) and subsequent rainfall events were modelled as described in Prediction 3 (using Equation 4.4) in Chapter 5.4. The calculation also assumed that the block surface area covered 85% of the total area of the structure.

A second assumption made was that if the amount of rainfall applied was less than the maximum block retention for a given storm duration, then the retention was 85% of the rainfall input (plus pre-storm retention).

Surface block evaporation.

Chapter 4.4.4 discussed the small-scale evaporation data which were best described by Equation 4.5. The small-scale evaporation experiments over-estimated block evaporation by approximately 26%. Equation 4.5 was used to model the evaporation from a car park surface but it was appreciated that this equation would need to be examined in more detail at a later stage in model development.

Total retention and evaporation.

The model prediction of total retention and total evaporation was based on the assumption that each box component (blocks or bedding material) acted as hydrologically independent components. To produce a prediction of total retention or evaporation, the model summed the two component values i.e.,

$$TR = BR + BMR \qquad \textbf{Equation 8.1}$$

where

BR = block retention

TR = Total Retention

BMR = bedding material retention.

8.6 How the model works - Equations used.

The model is essentially a set of simple empirical equation groups, the choice of which is determined by Boolean expressions (ie., if A = B then do C). A listing of the model is given in Appendix D. From the listing it is possible to identify the equations used to calculate the hydrological responses. Figures 8.1 and 8.2 show the model procedure. Figure 8.1 shows the prediction procedure on a dry surface and Figure 8.2 shows the procedure for predicting hydrological response on a surface containing pre-storm retention. This section explains the equations used by the model to predict the response.

Block retention.

Equations 8.2.a and 8.2.b were used to calculate the retention by the surface blocks on a dry surface.

BRET= (LOG(FR/60) / LOG(10)) * 37.04 + 68.8 **Equation 8.2.a**

BRETT= (BRET * (BEDAREA / 0.02) **Equation 8.2.b**

Where BRET= block retention (g) for a single block;

LOG= Qbasic expression to calculate logarithmic values;log to the base 10;

FR= storm duration (minutes);

BRETT= block retention (g) for the whole surface area

BEDAREA= bed area.

Equation 8.2.a is essentially Equation 4.4. Equation 8.2.b calculated the block retention for the surface area of the structure.

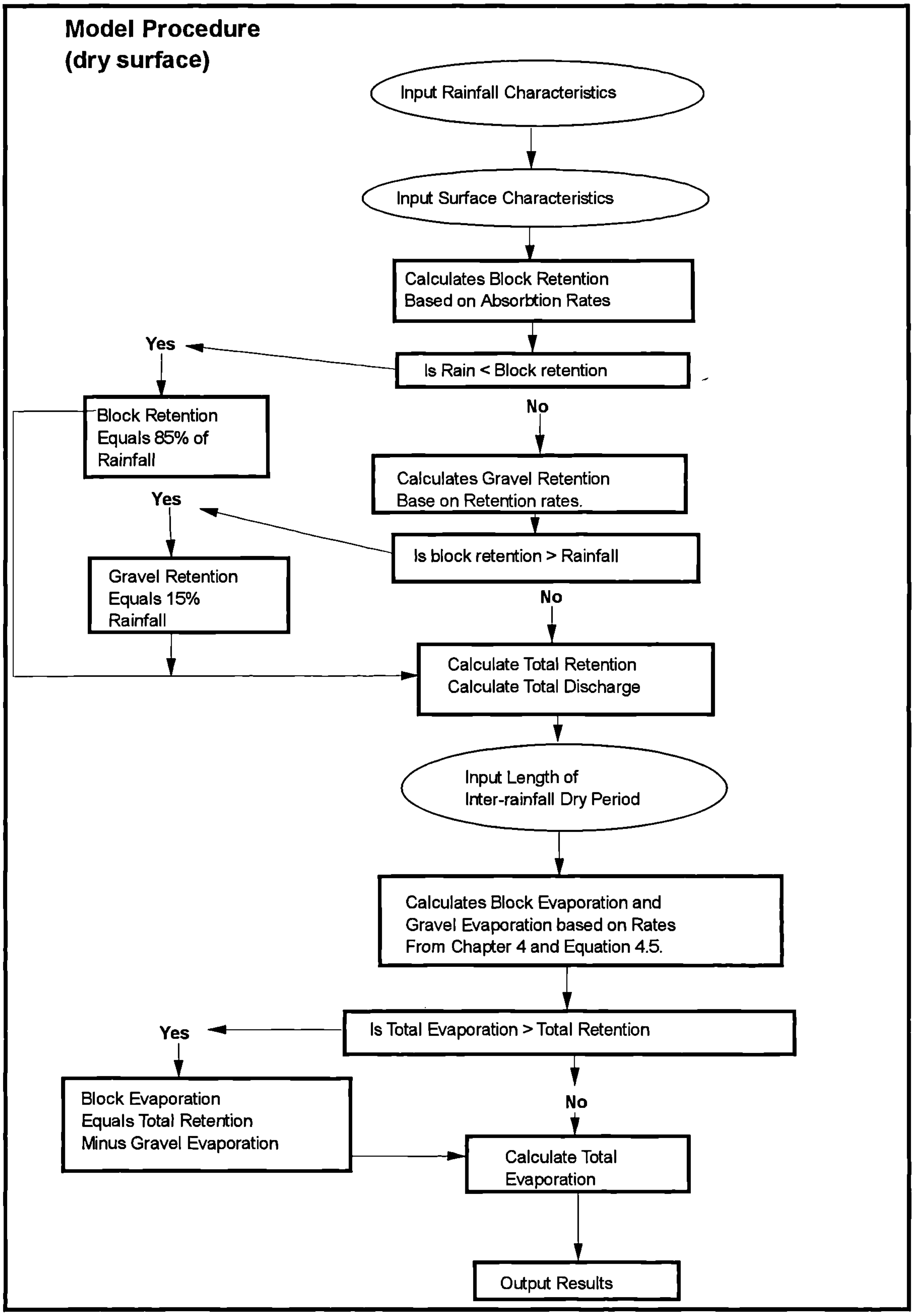


Figure 8.1 **Model procedure for a dry car park surface.**

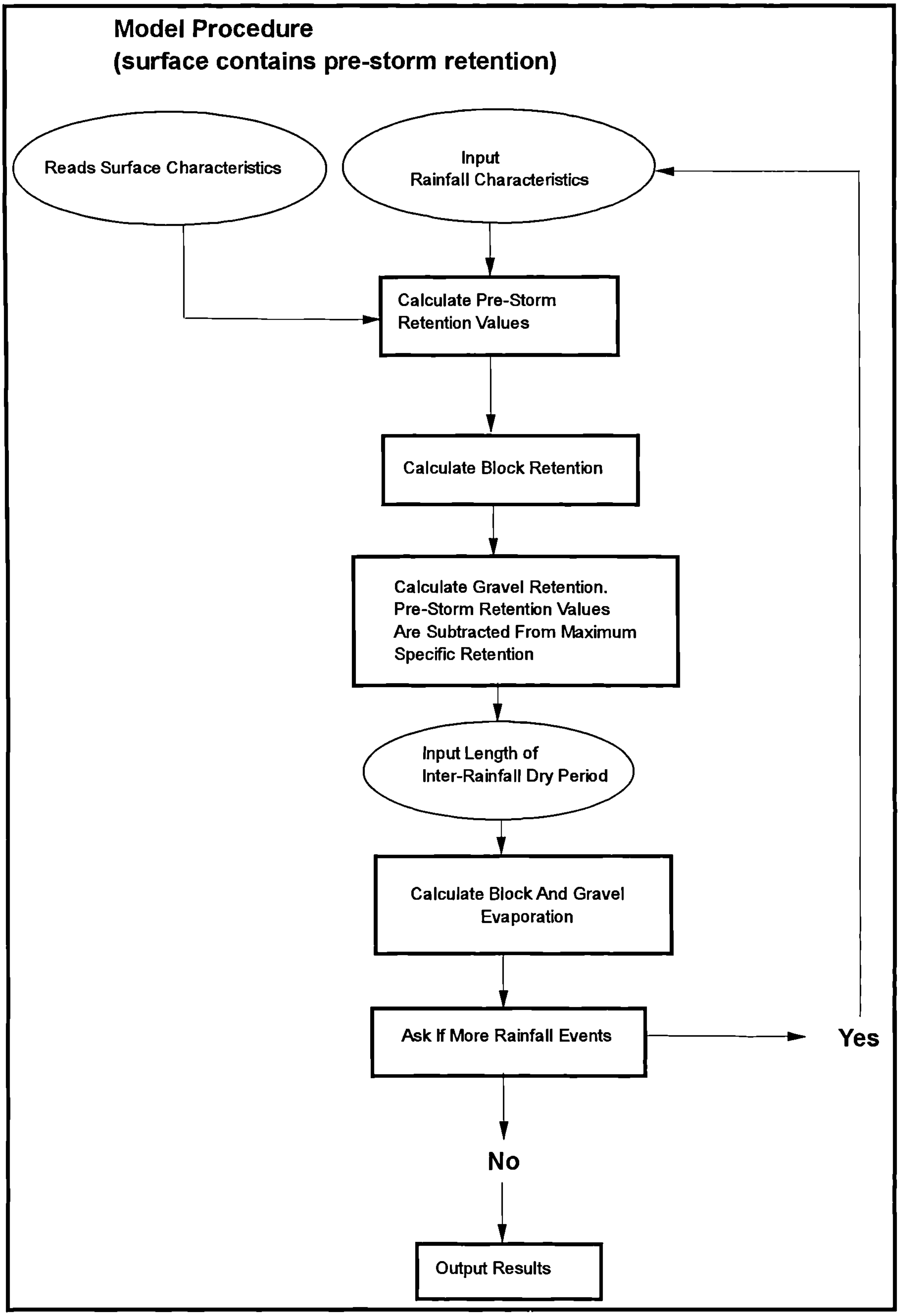


Figure 8.2 Model procedure for a surface containing pre-storm retention.

When the block surface had experienced previous rainfall events, the block retention was calculated from Equations 8.3(a-e);

B1= BRET - BEVAP	**Equation 8.3.a**
B2= (B1 - 68.8)/37.04	**Equation 8.3.b**
B3= 10^ (b2)	**Equation 8.3.c**
BRET2=(LOG((FR/60)+B3)/LOG(10))*37.04 +68.6	**Equation 8.3.d**
BRETT2= (BRET2 * (BEDAREA / 0.02)	**Equation 8.3.e**

Where B1= block retention (g) following a dry period

BRET= block retention (g) following the previous rainfall event;

BEVAP= block evaporation (g) after the last rainfall event;

B2= calculated variable of .log(t), where (t) is time;

B3=inverse (t) value of .log (t);

BRET2=block retention (g) following the next rainfall event;

FR= duration of the storm event (minutes);

BRETT2= the block retention (g) by the full surface area;

BEDAREA= surface area of the structure.

Equation 8.3.a calculated the block retention prior to the rainfall event. Equation 8.3.b then calculated the log(t) value for that retention. Equation 8.3.c inverses the B2 value to find the value of (t) which would produce the retention value (B1) when substituted into Equation 8.2.a. Equation 8.3.d calculated block retention. The (t) value was calculated by summing B3 and the subsequent storm duration time. Equation 8.3.e calculated the total retention in the surface.

Bedding material retention.

The model calculated the specific retention depending on the type and grain size of the bedding material. The model was written to store the following five bedding material variations;

1. Pea gravel grain size of 1-10 mm
2. Pea gravel grain size of 5-10 mm
3. Pea gravel grain size of 3-5 mm
4. Pea gravel grain size of 1-3 mm
5. Limestone grain size of 5-10 mm.

The model requested the choice of bedding material prior to model calculations. Each bedding material had a maximum specific retention which could not be exceeded. Equations 8.4.a and 8.4.b show how the specific retention (in grams) was calculated. Pea gravel, with a grain size of 1-10 mm, is used as an example.

Equation 8.4.a

If RAING < (((69.2 * (VOL/1000)) + (((0.15 * BEDAREA)*100) * 69.2)) + BRET

then WRET = (RAING - BRET) else go to next line

Equation 8.4.b

If RAING > (((69.2 * (VOL/1000)) + (((0.15 * BEDAREA) * 100) * 69.2)) + BRET)

then WRET = 69.2 * (VOL/1000) + (((0.15 * BEDAREA) * 100) * 69.2)

Where RAING= rainfall (g) during the event;

VOL= volume of gravel in the whole surface (l);

BEDAREA= surface area of the structure(m^2);

BRET= block retention by the surface area (g);

WRET= retention (g) by the bedding material in the whole of the surface.

Equation 8.4.a determined whether the rainfall applied (g) during the event was less then the maximum specific retention of the bedding material. If this was the case then the bedding material retention was calculated by subtracting block retention from the rainfall (i.e., block retention was calculated as 85% of the rainfall).

Equation 8.4.b determines whether the rainfall was greater then the maximum specific retention. If it was greater, then bedding material retention (WRET in g) was calculated by Equation 8.4.c:

Equation 8.4.c

WRET=**69.2** * (VOL/1000) + (((0.15 * BEDAREA) * 100) * **69.2**

The value in bold text is taken from Table 4.2 and this was varied depending on bedding material type and grain size. Equation 8.4.c also calculated the retention of the bedding material held in the infiltration inlets of the surface.

The model then calculated the equivalent specific retention in mm using Equation 8.4.d:

WRETMM = ((WRET / BEDAREA) / 1000) **Equation 8.4.d** where WRETTMM= retention by the bedding material in the whole surface in mm;

WRET= retention by the bedding material in the whole surface (g);

BEDAREA= area of the surface(m^2).

If bedding material retention was to be calculated for a surface which had pre-storm retention, the model used a different calculation. Under these circumstances bedding material retention was calculated by Equation 8.5.a and 8.5.b:

Equation 8.5.a

If RAING2 < (((69.2 * (VOL/1000)) + ((0.15 * BEDAREA)* 100 * 69.2) + BRETT2)

then WRET = (RAING2 - BRETT2) + GRET1 else next line

Equation 8.5.b

If RAING2 >(((69.2 * (VOL/1000) + ((0.15 * BEDAREA) * 100) * 69.2 + BRETT2)

then WRET2 =(69.2 *(VOL/1000)) + (((0.15 * BEDAREA) *100) * 69.2)

Where

RAING2= rainfall (g) for the rainfall event;

BEDAREA= surface area of the structure(m^2);

BRETT2= block retention after this event (g);

WRET2= bedding material retention for the event (g);

GRET1= pre-storm retention in the bedding material prior to the rainfall (g).

Equation 8.5.a shows that if the rainfall was less then the maximum specific retention by the bedding material, the bedding material retention equalled 15% of the rainfall plus the pre-storm retention in the bedding material. The retention by the bedding material (using Equation 8.5.a) may be in excess of the maximum specific retention. The model checked this by the Boolean expression given in Equation 8.5.c;

Equation 8.5.c

IF WRET2 >(69.2 * (VOL/1000))+(((0.15 * BEDAREA) * 100)* 69.2) then WRET2 =(69.2*(VOL/1000))+(((0.15 * BEDAREA) * 100)* 69.2)

i.e, if the calculated bedding material retention was greater then the maximum retention, then the bedding material retention is set to the maximum.

Block evaporation predictions.

Block evaporation from the total surface area was calculated from Equation 8.6.a, 8.6.b and 8.6.c;

BEVAP=(LOG(IRP/60) / LOG(10))* 36.41 - 41.62 **Equation 8.6.a**

BEVAPT= BEVAP * (BEDAREA / 0.02) **Equation 8.6.b**

BEVAPTMM= (BEVAPT / BEDAREA) / 1000 **Equation 8.6.c**

Where BEVAP= block evaporation (g);

IRP= inter rainfall dry period (minutes);

BEVAPT= block evaporation (g) from the whole surface area;

BEDAREA= area of the surface;

BEVAPTMM= block evaporation from the surface in mm.

Equation 8.6.a is the Qbasic form of Equation 4.5. This equation calculated evaporation from a single block. Equation 8.6.b calculated evaporation (g) from the whole surface area which was then converted into mm equivalent depth of rainfall by Equation 8.6.c.

Bedding material evaporation predictions.

The model calculated evaporation from five different bedding materials, the choice of which was determined prior to calculation. Evaporation from each bedding material grain size and type was based on a unique equation. The amount evaporated depended on the length of the dry period and the surface area of the structure. Figure 8.3 shows part of the program listing, to show how bedding material evaporation was calculated in the model. Line 1010 used a set of Boolean expressions to determine which bedding material had been selected. This was governed by both the grain size and type of bedding material. For example, if the pea gravel with a grain size of 1-10 mm was selected the model would use the calculation of line 1100. The next stage of the model calculation is determined by the inter rainfall dry period. The dry period was broken down into minute time steps (IRP) and, depending on the value of IRP, the model was directed to the appropriate calculation. For example if IRP was 370 minutes long, the programme would move onto line 1290. The "gevap" value would then be calculated. The "gevap" value was the calculated evaporation (g) from a small scale sample based on results presented in Chapter 4 (Table 4.3.A). The "gevap" value is then scaled up to 15% of the surface area of the structure (line 3000) and converted into mm equivalent depth of rainfall (in line 3002).

Figure 8.3 Listing of a section of program.

```
1010 IF A$ = "L" OR A$ = "L" AND A = 1 THEN GOTO 2600
1020 IF A$ = "P" OR A$ = "P" THEN GOTO 1021
1021 IF A = 1 THEN GOTO 1110
1030 IF A = 2 THEN GOTO 1455
1040 IF A = 3 THEN GOTO 1800
1050 IF A = 4 THEN GOTO 2200
1100 REM PEA GRAVEL SELECTION (1) CALCULATIONS 1-10 MM
1110 IF IRP > 0 AND IRP <= 60 THEN GOTO 1120 ELSE 1140
1120 GEVAP = ((.13 / 60) * IRP)
1140 IF IRP > 60 AND IRP <= 120 THEN GOTO 1150 ELSE 1170
1150 GEVAP = (((.04 / 60) * (IRP - 60)) + .13)
1170 IF IRP > 120 AND IRP <= 180 THEN GOTO 1180 ELSE 1200
1180 GEVAP = (((.09 / 60) * (IRP - 120)) + .17)
1200 IF IRP > 180 AND IRP <= 240 THEN GOTO 1210 ELSE 1230
1210 GEVAP = (((.08 / 60) * (IRP - 180)) + .26)
1230 IF IRP > 240 AND IRP <= 300 THEN GOTO 1240 ELSE 1260
1240 GEVAP = (((.07 / 60) * (IRP - 240)) + .34)
1260 IF IRP > 300 AND IRP <= 360 THEN GOTO 1270 ELSE 1290
1270 GEVAP = (((.06 / 60) * (IRP - 300)) + .41)
1290 IF IRP > 360 AND IRP <= 420 THEN GOTO 1300 ELSE 1320
1300 GEVAP = (((.05 / 60) * (IRP - 360)) + .47)
1320 IF IRP > 420 AND IRP <= 480 THEN GOTO 1330 ELSE 1350
1330 GEVAP = (((.045 / 60) * (IRP - 420)) + .52)
1350 IF IRP > 480 AND IRP <= 540 THEN GOTO 1360 ELSE 1380
1360 GEVAP = (((.04 / 60) * (IRP - 480)) + .565)
1380 IF IRP > 540 AND IRP <= 600 THEN GOTO 1390 ELSE 1410
1390 GEVAP = (((.3 / 60) * (IRP - 540)) + .605)
1410 IF IRP > 600 AND IRP <= 3720 THEN GOTO 1420 ELSE 1430
1420 GEVAP = (((.012 / 3120) * (IRP - 600)) + .635)
1430 IF IRP > 3720 THEN GOTO 1440
1440 GEVAP = (((.01 / 11280) * (IRP - 3720)) + .647)
1445 GOTO 3000

3000 GEVAPT = ((BEDAREA * 10000) / 8.55) * GEVAP
3002 GEVAPTMM = (GEVAPT / BEDAREA) / 1000
```

8.7 Model Results - Predictions.

The hydrological performance of six boxes (discussed in Chapters 5 and 6) were chosen for comparison with model predictions. The boxes, their contents, the rainfall applications, and inter-rainfall dry periods for each run are summarised in Table 8.1.

All of the boxes were chosen for comparison because they contained one bedding material with one grain type and size. The input data of Table 8.1 were fed into the model and predictions of the hydrological response were calculated. The predicted hydrological response of each box produced by the computer model was compared to the observed hydrological performance. Table 8.2 gives the discharge, retention and evaporation values for all 3 runs and all boxes examined. To assess the degree of similarity between the predicted and the observed, the percentage error was calculated using Equation 8.7:

Error function = ((Vp - Vo)/ Vo) x 100 **Equation 8.7**

Table 8.1. Experimental statistics from previous box experiments.

	Box 2	Box 3	Box 5	Box 6	Box 7	Box 10
Box components	Pea gravel (1-10 mm) depth of 50 mm and blocks.	Pea gravel (1-10 mm) depth of 30 mm and blocks.	Pea gravel (5-10 mm) depth of 50 mm and blocks.	Pea gravel (3-5 mm) depth of 50 mm and blocks.	Pea gravel (1-3 mm) depth of 50 mm and blocks.	Limestone (5-10 mm) depth of 50 mm and blocks.
Rainfall Run 1 Run 2 Run 3	 15.00 15.09 15.00	 15.00 15.00 15.11	 15.00 15.00 15.03	 15.00 15.00 15.03	 15.00 15.39 15.00	 15.00 15.33 15.04
Length of dry period (hours) Run 1 Run 2 Run 3	1027 314 816	698 315 430	747 289 812	737 288 908	768 257 816	765 286 796

Table 8.2. **The predicted and observed discharge, retention and evaporation for the boxes chosen for comparison.**

Units (mm)	Box 2 O	Box 2 P	Box 3 O	Box 3 P	Box 5 O	Box 5 P	Box 6 O	Box 6 P	Box 7 O	Box 7 P	Box 10 O	Box 10 P
Discharge												
Run 1	5.9	7.1	5.9	8.5	7.8	8.6	7.3	5.0	2.6	2.9	8.0	7.9
Run 2	8.3	12.1	8.5	12.3	9.5	12.2	10.0	12.3	6.3	12.6	10.0	12.5
Run 3	13.3	11.3	14.3	11.4	11.6	11.4	11.0	11.4	9.4	11.4	11.6	11.4
Retention												
Run 1	9.1	7.9	9.1	6.6	7.2	6.4	7.7	10.0	12.4	12.1	7.0	7.1
Run 2	11.6	7.4	11.5	6.0	8.9	5.9	9.1	9.5	14.7	11.5	8.6	6.6
Run 3	12.8	8.5	12.2	7.1	9.5	7.0	10.6	10.6	15.8	12.6	9.4	7.7
Evaporation												
Run 1	4.3	3.5	4.1	3.2	3.8	3.3	3.6	3.3	5.9	3.4	3.7	3.3
Run 2	4.3	2.6	4.1	2.6	2.8	2.5	2.5	2.5	4.5	2.4	1.6	2.5
Run 3	6.1	3.3	5.4	2.8	4.2	3.4	7.1	3.4	5.6	3.4	4.8	3.4
Percentage difference		(%)		(%)		(%)		(%)		(%)		(%)
Discharge												
Run 1		19.7		43.2		10.3		-31.9		12.7		-1.6
Run 2		45.8		44.8		28.7		22.6		99.5		25.3
Run 3		15.0		20.1		1.8		3.7		21.5		-1.7
Retention												
Run 1		-12.8		-28.0		-11.1		30.3		-2.7		1.9
Run 2		-36.2		-47.6		-33.9		4.4		-21.5		-23.1
Run 3		-33.5		-41.6		-26.6		0.0		-20.0		-18.1
Evaporation												
Run 1		-18.1		-21.5		-13.4		-9.4		-43.2		-10.3
Run 2		-40.0		-37.1		-9.3		0.8		-45.8		58.8
Run 3		-45.3		-47.6		-20.0		-51.7		-39.1		-30.2

where;

Vp = predicted value by the computer;

Vo = Observed value.

The percentage differences are given in Table 8.2.

Discharge predictions.

The predicted discharge values were plotted against the observed values and are shown in Figure 8.4. Lines were also plotted to show a perfect prediction and over - (20% and

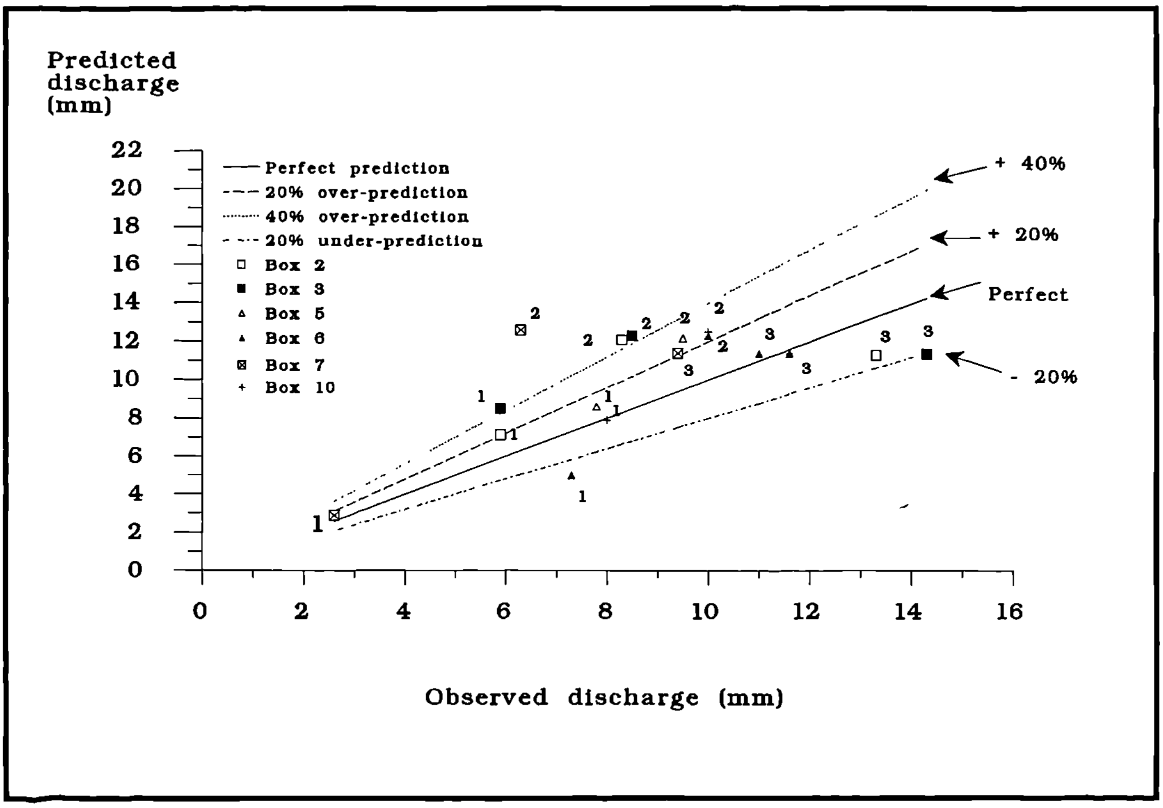


Figure 8.4 **The relationship between predicted model discharge and observed discharge.**

40%) and under-estimations (20%) of discharge. The numbers next to the symbols in Figure 8.4 denote the Run number (i.e., Run 1, Run 2 and Run 3).

In general the model has a tendency to over-estimate discharge (only 6 out of 18 predictions lie on the negative side of the perfect prediction line). The scatter in the predicted values is also influenced by the run number, with the highest over-prediction associated with Run 2, which differed from the other 2 runs by having the shortest storm duration. The only variable to change during each run was the storm duration. The only component which used storm duration to calculate the hydrological performance was the surface blocks. The retention of the surface blocks was dependent on storm duration. Since discharge is a function of retention, it is suggested that the retention of water by the surface blocks was one area in the model which may produce errors in predictions by under-estimating retention, thus producing over-estimations in discharge.

Retention predictions.

Figure 8.5 shows the predicted retention values plotted against the observed retention values. Again a line for a perfect prediction has been shown as well as for a 20% and 40% under-prediction.

Figure 8.5 effectively is the reciprocal of discharge since discharge is a function of retention. There is a tendency by the model to under-estimate retention by around 20%.

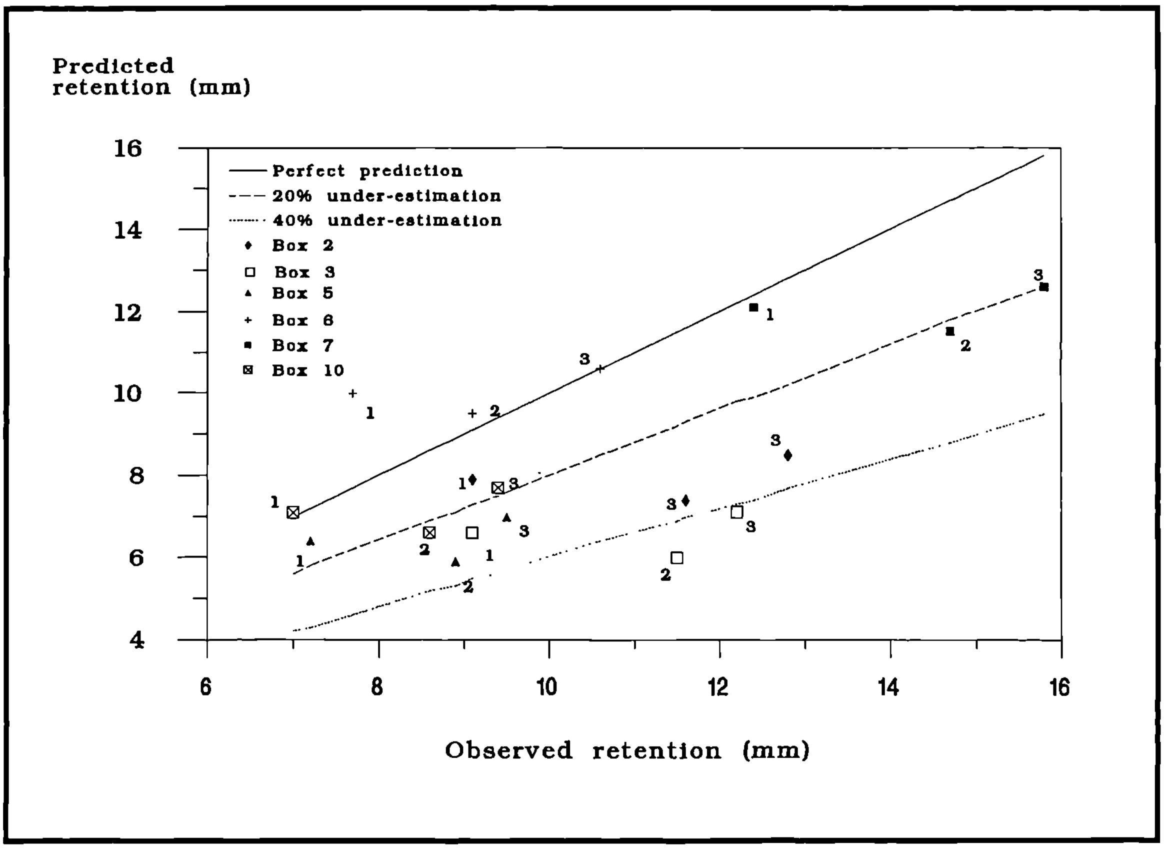


Figure 8.5 The relationship between the predicted model retention and the observed retention.

The influence of the run on the scatter is not as obvious as in Figure 8.4 which may be a result of pre-storm retention masking the influence of storm duration on retention during single events. The best predictions were for Box 6.

Evaporation predictions

Figure 8.6 shows the relationship between the predicted and the observed evaporation rates. Here, the prediction is poor. The under-estimation of evaporation appears to be the worst factor in the model. The procedure estimated evaporation by assuming that the two box components acted as hydrologically independent units. Whilst this may be convenient for modelling, it may not be a good representation since the two components may interact more than is assumed.

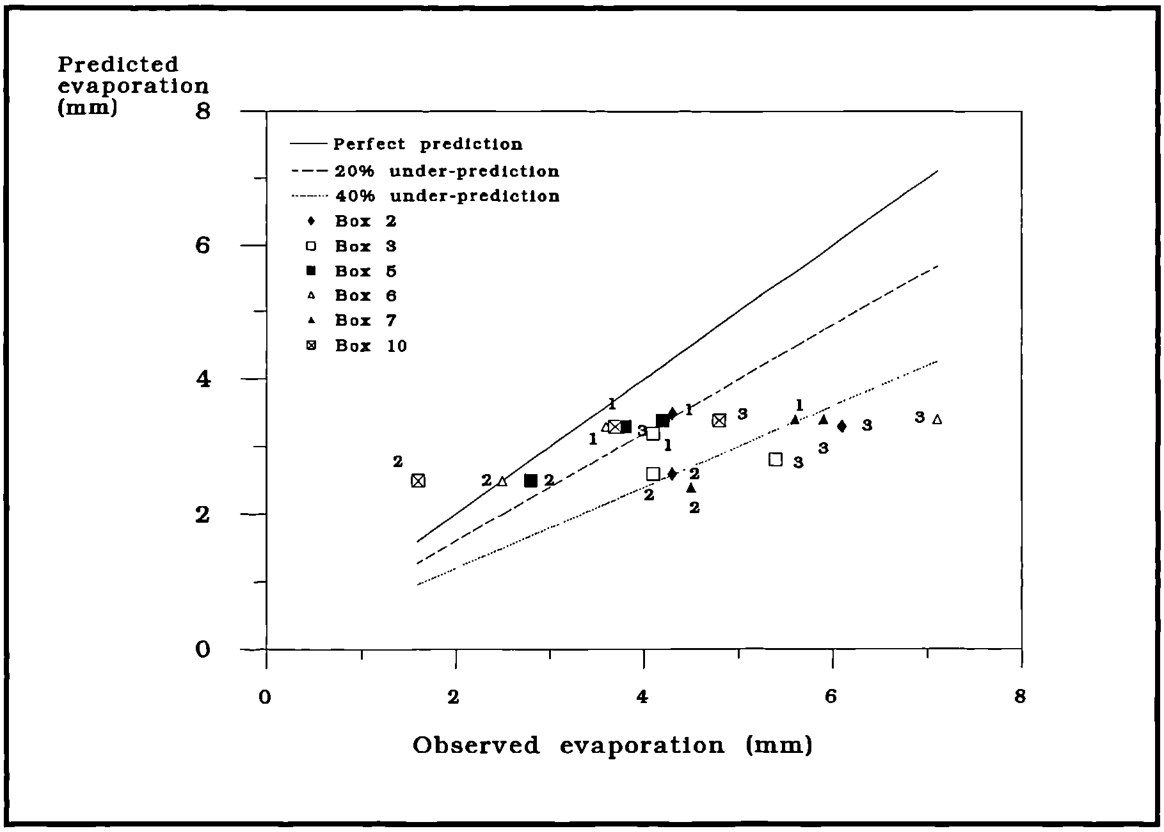


Figure 8.6 The relationship between the predicted and observed evaporation by the model boxes.

Improving model fit.

The percentage error values given in Table 8.2 and the data illustrated in Figures 8.4 to 8.6 identified two main areas where the model predictions required improvement;

1) evaporation predictions;

2) retention by the surface blocks.

Improvements to the evaporation predictions.

The predictions of evaporation by the model were seen to be the poorest of all predictions. The method of calculating evaporation assumes the bedding material and surface blocks act independently, evaporating water at differing rates. This is further complicated by the varying evaporation rates of the bedding materials. In Chapter 6.3.4, a multiple regression analysis was presented which described evaporation by Equation 6.6. the regression analysis explained 62% of the variation in evaporation from all of the model boxes over all runs. It was decided, therefore, that Equation 6.6 would be inserted into the computer model in order to see if better predictions of evaporation could be achieved. Evaporation in the model was subsequently calculated using Equation 8.8;

$$E=0.04519 + (0.27465 \times RET) + (0.002445 \times IRP) \qquad \textbf{Equation 8.8}$$

where

RET = retention by the structure (mm);

E = evaporation (mm);

IRP = dry period (hours).

The predicted evaporation rates were plotted against the observed evaporative rates (Figure 8.7). In comparison with Figure 8.6, it is immediately apparent that the predictions are a considerable improvement over the initial model (see Appendix D for the full listing). There was significantly less scatter and most points centred around the perfect prediction line. The percentage error was calculated using Equation 8.7 and plotted in Figure 8.8. Figure 8.8 also shows the percentage error of the first model predictions (prediction 1). 15 out of the 18 predictions show an improvement after the model had been modified.

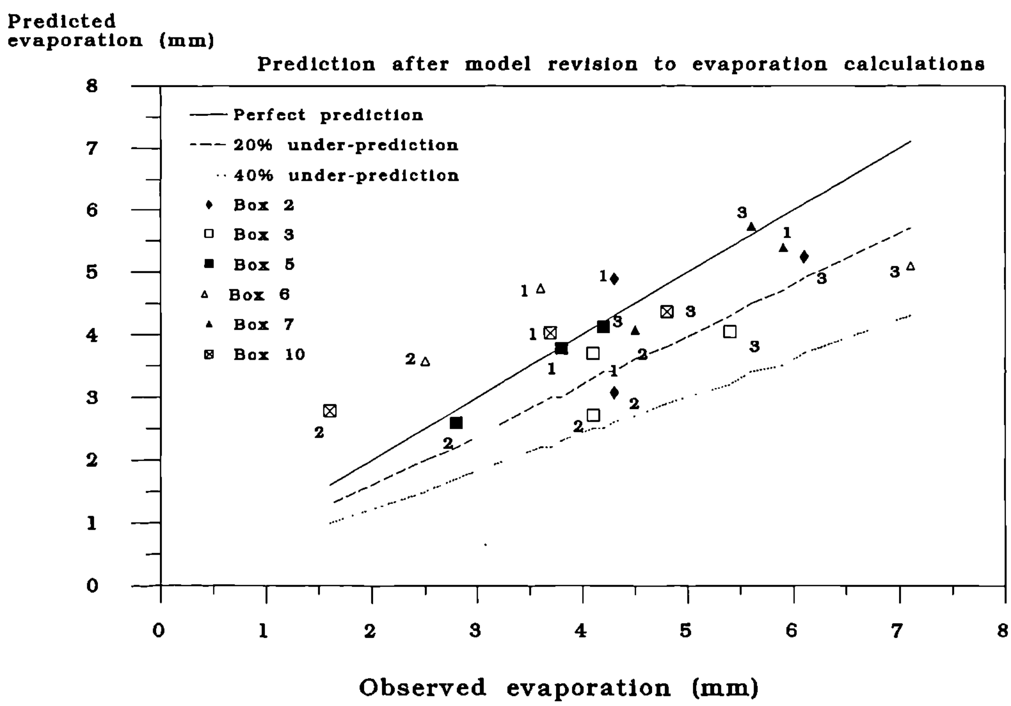


Figure 8.7 The relationship between predicted and observed evaporation after modification to the model.

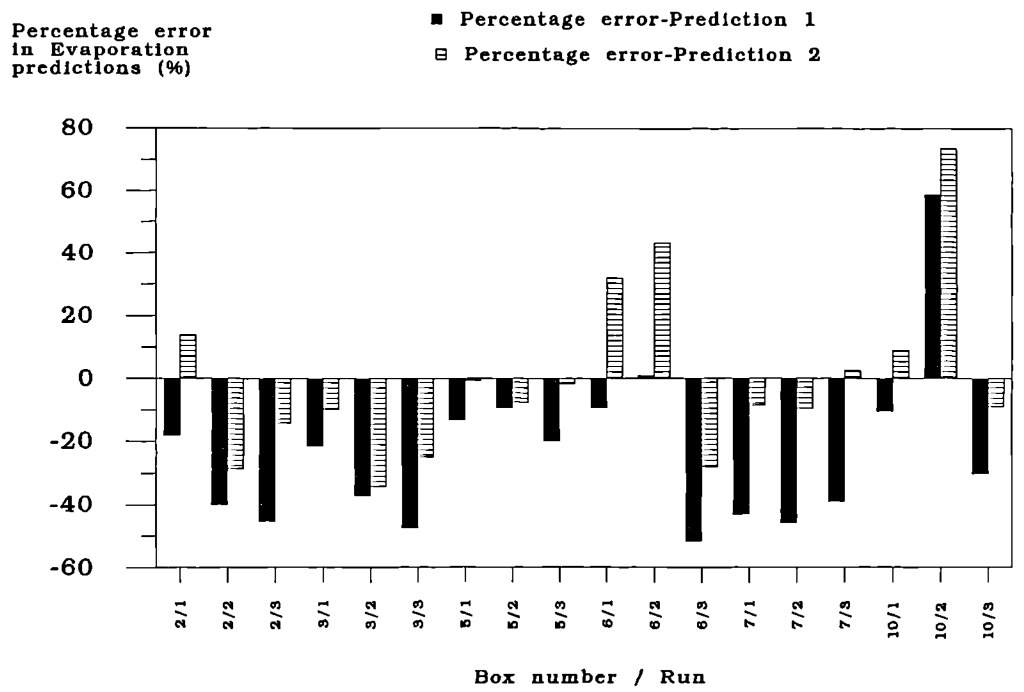


Figure 8.8 Percentage errors in evaporation predictions before and after model modifications.

Improvement to block retention predictions.

In Chapter 5, a comparison was made between the observed and the predicted retention of the surface blocks. The results (Table 5.9(I)) suggested that the predictions for the first rainfall events under-estimated block retention by 16.28%, 29.52% and 25.88% for Runs 1, 2 and 3 respectively with an average under-prediction of 29.32%. In order to improve the predictions of block retention, the model was modified to take account of these under-estimates. All block retention predictions were therefore multiplied by 1.29 (accounting for the average 29% under-estimation). Figure 8.9 shows the predicted values plotted against the observed values. Even with the changes to the calculations, the model had a tendency to under-estimate retention. However, the percentage error was generally reduced, as shown in Figure 8.10.

Figure 8.10 shows that 11 out of the 18 predictions of retention were improved with these changes to the model. It was also visible that the model still under-estimated retention, except for Box 6 (Runs 1 to 3) and Run 1 for Box 10.

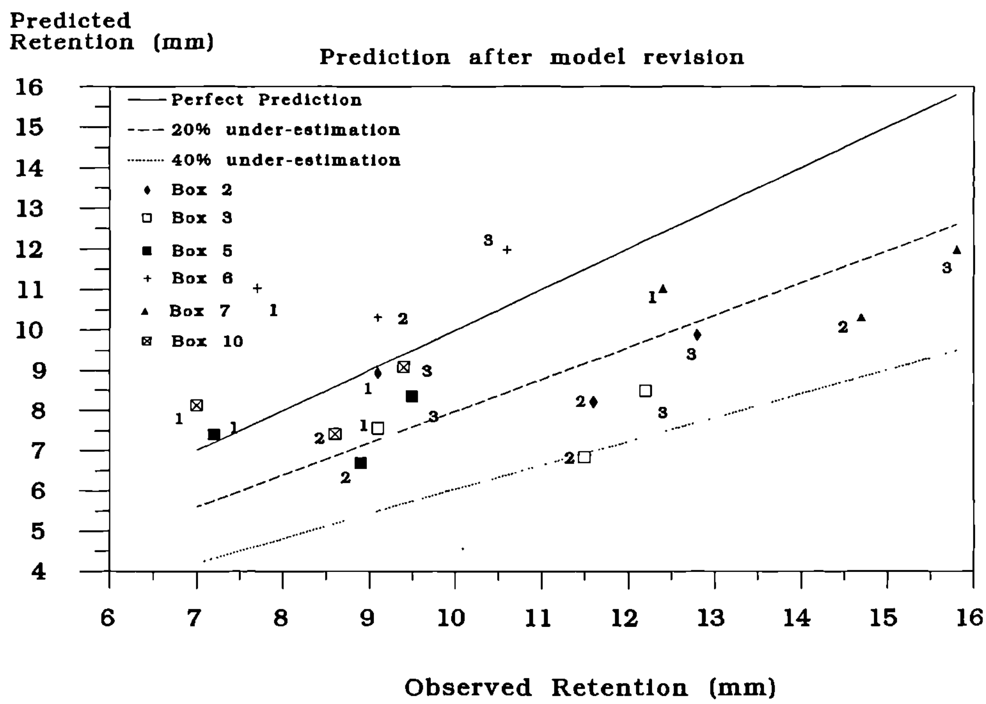


Figure 8.9 **The relationship between the predicted and observed retention after model modification of block retention calculations.**

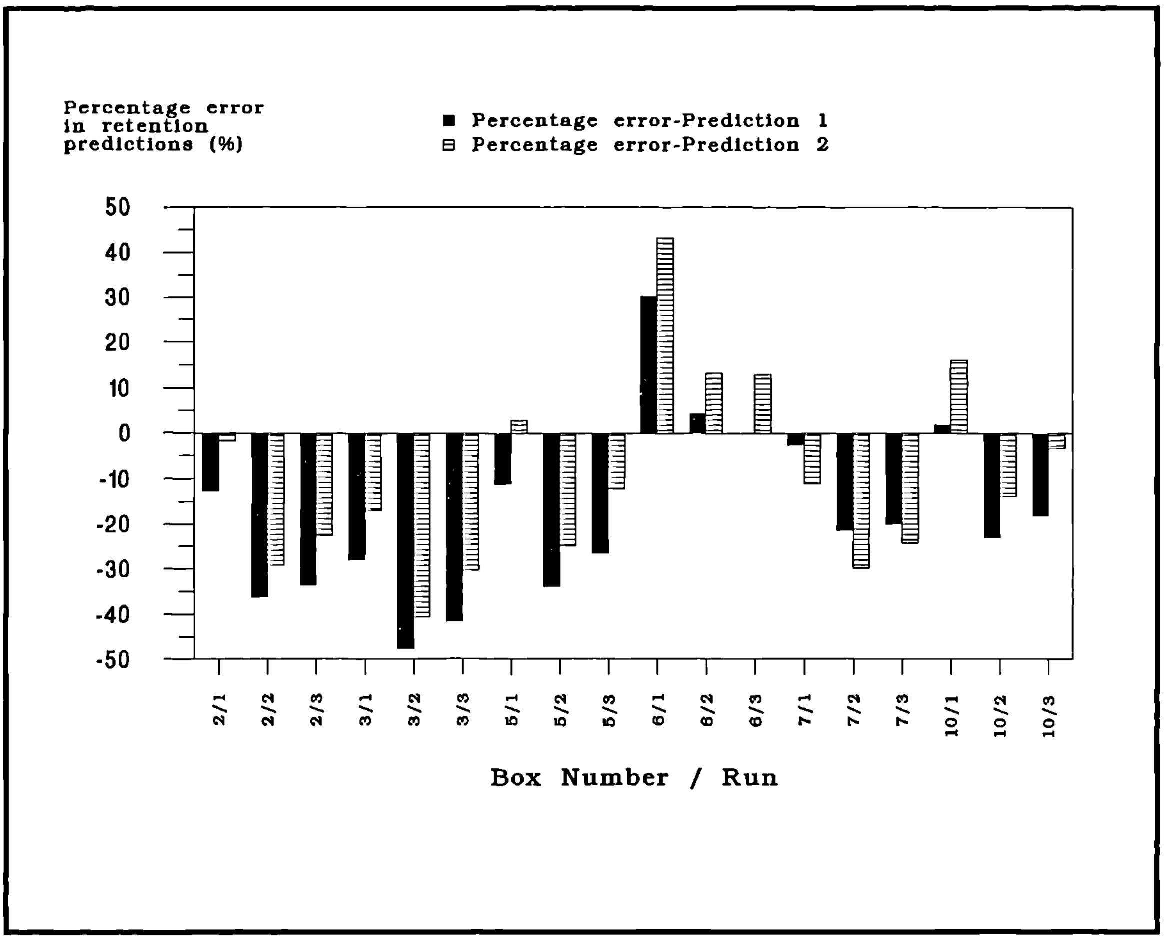


Figure 8.10 **Percentage error in retention predictions before and after modifications to the model.**

8.8 The model - a predictive tool ?.

The final model used a set of empirical calculations to determine an output from a set of input values. It is a simple method for predicting hydrological performance based largely on a number of small-scale experiments. Whilst the main aim of this chapter was not to fully optimise the model, a number of improvements in the model performance were achieved by accounting for scale effects in retention calculations and using a simple model for predicting evaporation from both the surface blocks and bedding material components.

Table 8.3 **The percentage differences for Predictions 1 and 2 from the observed.**

Box Number	2	2	3	3	5	5	6	6	7	7	10	10
P	1	2	1	2	1	2	1	2	1	2	1	2
R												
Run 1	-12.8	-1.8	-28.0	-17.0	-11.1	2.8	30.3	43.25	-2.7	-11.1	1.9	16.1
Run 2	-36.2	-29.1	-47.6	-40.6	-33.9	-24.9	4.4	13.3	-21.5	-29.9	-23.1	-13.8
Run 3	-33.5	-22.7	-41.6	-30.3	-26.6	-12.1	0	13.0	-20.0	-24.2	-18.1	-3.4
E												
Run 1	-18.1	13.7	-21.5	-9.8	-13.4	-0.5	-9.4	31.9	-43.2	-8.6	-10.3	8.9
Run 2	-40.0	-28.6	-37.1	-34.2	-9.3	-7.5	0.8	43.2	-45.8	-9.6	58.8	73.8
Run 3	-45.3	-14.1	-47.6	-25.0	-20.0	-1.7	-51.7	-28.2	-39.1	2.5	-30.2	-9.0

P= prediction; E= evaporation; R= retention.

To compare the model predictions before and after modifications, the average percentage differences were calculated. Table 8.3 gives the percentage differences for predictions 1 and 2 compared with the observed retention and evaporation.

The average percentage difference was calculated for both predictions for retention and evaporation. The average percentage difference for the retention and evaporation predictions were 21.85% for retention prediction 1 and 30.09% for evaporation predictions 1. After the model was modified and the second predictions were produced, the average percentage differences changed to 19.42% for the retention prediction and 19.48% for the evaporation prediction. Both modifications to the model increased the accuracy of predictions.

As a predictive tool, the model performs well, giving over 80% accuracy in predictions for evaporation and retention. Considering that the data used in the model was taken from small-scale experiments which could be conducted in the laboratory within 2 weeks, the model provides a simple and effective tool for predicting the hydrological response of a model car park surface. Further optimisation could improve the accuracy of predictions but it was not the aim of this research to produce such a model. Instead, this research has been successful in providing a design tool (which uses easily obtainable data) which can predict the evaporation and retention processes in a model car park surface.

8.9 Summary

This chapter has described an empirical model which has been developed from the research findings of previous chapters. The research has provided insight into the ways in which structural components influence these hydrological processes. A consideration of the way that structural components influences these processes has been valuable in aiding the construction of empirical equations to predict process response. The accuracy of predictions of retention and evaporation was good even before model optimisation. It is recommended that this model be used as a design tool for engineers wishing to construct a porous pavement.

Chapter 9 - Conclusions

9.1 Discussion and Conclusions.

The results presented in Chapters 4 to 8 were concerned with four main areas of research including;

1) the hydrological performance of the single structural components (Chapter 4);
2) the hydrological performance of the total car park structures (Chapters 5 and 6);
3) the effect of clogging on the hydrological car park performance of the structure (Chapter 7);
4) the development of a predictive model based on (1) above and validated using the data gathered in (2) above (Chapter 8).

This chapter aims to discuss the importance of the results obtained with regard to the use of permeable pavements in the control of urban stormwater runoff and identify the broader significance of this performance in relation to urban hydrological cycle as discussed in Chapter 2.

9.2 Hydrological Performance of Single Box Components.

The analysis of individual components of the car park structure showed that the surface blocks and the bedding materials performed differently. The retention by the surface blocks was strongly influenced by the contact time with water; some 60% of the total amount of water absorbed in 1 hour occurred in the first 5 minutes of contact. This suggested that storm duration would be an important influence on the total amount of water retained by the surface blocks and subsequently evaporated from the structure.

Evaporation amounts from the surface blocks were seen to be lower than the bedding material, being on average 33% lower over a 17 day period. Evaporation experiments on the blocks showed that 47% of the water evaporated during the first 21 days was evaporated during the first three days. This demonstrated that the presence of the blocks reduces evaporation and, as a result, might suggest that the hydrologically optimum surface should be made of only bedding material. However, such a construction would have two major disadvantages. Firstly, it would have a lower structural strength than the block surface and, secondly, it would significantly decrease the ability of the structure to retain water. It may be advantageous in subsequent research to optimise the design of the surface blocks in order to increase the percentage of the surface area covered by the infiltration inlets whilst retaining structural integrity for load bearing.

The bedding material experiments have shown that differing grain sizes will influence the total retention and evaporation. A small grain size (1-3 mm) was identified as being more efficient at retaining rainfall and increasing the rate and total amount of evaporation from the surface when compared to larger sizes (3-5 and 5-10 mm). This agrees with the theory outlined in Chapter 4 (section 1) where smaller sizes of bedding material have a larger specific surface to retain water.

Calculations based on data from the hydrological performance of the individual components were compared with the actual performance of boxes containing similar components and the performance was shown to be similar. However, the calculated values were usually lower than the box data which suggests that scale effects are important in the context of these experiments.

9.3 Hydrological Performance of the Car Park Structures.

From the short term analysis on hydrological performance (Chapter 5), it was shown that total water retention was influenced by both blocks and bedding material in that the presence of blocks increase the potential for water retention, as did a smaller grain size. The most significant single component was the blocks although the effect decreased over rainfall events. Grain size of the bedding material was also important, with the smaller grain sizes retaining more water, and this factor was more important than lithology. Table 9.1 illustrates the total retention of rainfall by each box for each rainfall event as a percentage of the total rainfall applied (based on previous results from Chapter 7). The time interval between each rainfall simulation (runs 1-3) is also shown. These results indicate that if the car park structures are dry, on average 55% of a 15 mm h^{-1} rainfall event will be retained by the structure, thus providing a significant reduction in

Table 9.1. Rainfall retained as a percentage of the total rainfall applied during each simulation (the days between each run is referred to as the inter-rainfall dry period).

Box	Run 1	Days between Runs	Run 2	Days between Runs	Run 3
2	60.7%	44	45.4%	13	35.8%
3	60.5%	29	43.2%	13	32.1%
4	53.2%	29	34.4%	13	22.1%
5	47.9%	31	36.7%	12	22.5%
6	51.3%	31	33.3%	12	26.9%
7	82.7%	32	60.9%	11	37.6%
8	52.7%	31	36.7%	12	21.3%
9	39.7%	32	30.6%	12	27.2%
10	46.6%	32	35.4%	12	22.7%
Average	**55%**	**32**	**39.6%**	**12**	**27.6%**

runoff, even if the discharge from the structure is directed into a drainage system. The runoff ratio could be further decreased by using a smaller grain size of bedding material. If on-site infiltration is allowed, then the retention will be 100%. These structures can reduce the total volume of stormwater runoff and, if the percolating water needs to be evacuated from the structure, will at worst attenuate the storm hydrograph peak. The delay and reduction in the amount of water reaching the drainage system will undoubtedly decrease the stress on existing sewer systems and will have important downstream consequences (see Chapter 2 section 2.1.2).

The total retention of water in the bedding material voids is, on average, 42% of the gravel volume. If the base of the structure was sealed, for example, to allow water to be retained for evacuation through a grey water system, a surface area of 12.94 m^2 (the equivalent area of a car parking space) with a depth of bedding material of 50 mm, could store the equivalent depth of 21.01 mm of rainfall. This calculation does not include the additional retention which may be created by the presence of a sub-matrix material, which usually has a greater depth then the bedding material.

Evaporation from a structure during the inter-rainfall period is important since it governs the pre-storm retention held in the structure. This in turn influences discharge and retention volumes. Factors influencing evaporation from the surface are surface components (presence of blocks and the grain size of bedding material) and the length of the dry period. 9% of the rainfall retained in the structure was evaporated after the first day and approximately 30% after 15 days. Evaporation amounts from the structure was observed as being dependent on water availability.

The construction of the surface is important since this is where evaporation takes place. From the experimental results it is possible to design a surface which evaporates "efficiently". For example, the box experiments showed that evaporation was highest for the 1-3 mm grain size bedding material. If the smaller grain size bedding material is placed in the infiltration inlets, it may be possible to increase evaporation rates from the surface (in comparison with using a larger grain size of material). The ability of the structure to retain rainfall and then allow evaporation to take place will reduce the volume of water reaching the drainage system. It will also increase the retention capability of the structure for the next rainfall event.

9.4 The effect of clogging on hydrological performance.

Total clogging of the car park surface is difficult to achieve, even after an intense application of particulate material estimated to be equivalent to over 100 years of sediment load. Clogging, both on the experimental models and at the field sites, was seen to be concentrated in the upper 50 mm of the infiltration inlets which reduced the infiltration capacity of the structure. However, the infiltration capacity was seen to be above design parameters (greater then 13 mm h^{-1}), even after the heaviest sediment loads were applied. The field sites also showed that the structure maintained a high infiltration capacity (greater than 100 mm h^{-1}) after 8 years with no maintenance.

The results from the clogging experiments showed that the hydrological performance of the car park surface was improved in relation to the amount of water retained and through higher evaporative rates. Indeed clogging might be seen as an advantage rather than a disadvantage when using this structure providing that infiltrations rates do not fall below the minimum design requirements.

9.5 Development of a predictive model.

Chapter 8 discussed the development of a model which was used to predict the hydrological performance of the car park structure. The model was a design tool produced to aid the engineer in optimising the choice of structural components and assess their performance under varying rainfall conditions. Results indicated that the model was accurate to approximately 78% on discharge predictions, approximately 80% on retention predictions and around 80% on evaporation estimates. The raw data used to produce the model equations were taken from the small-scale experiments detailed in Chapter 4. This means that after less then 2 weeks laboratory work, sufficient information can be obtained from individual structural components which can incorporated into the model and used to predict hydrological performance of the car park structure with a reasonable degree of confidence. The model is simple in form and effective in producing a guide to the hydrological performance of any car park surface using different types of bedding material. This research project has yielded valuable information on the hydrological performance of a car park surface which can be used to design future structures. The results indicate that this permeable pavement can attenuate storm hydrographs; the degree of attenuation being determined by the structural components. The structure also has an evaporative efficiency (evaporating the water retained) of over 70% over the experimental period, thus allowing it to retain a high proportion of rainfall during subsequent events. The structure is simple to construct and is effective at ameliorating the hydrological problems associated with urbanisation, potentially, maintaining pre-development hydrological pathways in a "quasi-natural" hydrological cycle.

9.6 Control of urban runoff through the use of permeable pavements

In Chapter 2 impermeable surfaces associated with urbanisation were shown to influence urban runoff by affecting:

1) the quantity of stormwater runoff;
2) the quality of stormwater runoff.

9.6.1 Controlling the quantity of urban runoff by using permeable pavements.

As discussed in Chapter 2, impermeable surfaces decrease infiltration and percolation rates, throughflow volumes and reduce the quantity of water reaching the aeration zone (Field *et al.* 1982). These surface also reduce the amount of water recharging groundwater and it's subsequent availability for abstraction (Schumm, 1977; NRA, 1992). Furthermore, urban runoff from impermeable surfaces will contribute to a greater amount of overland flow (Horton, 1933; Walling, 1981) which increases the risk of flooding in urban areas (Walling, 1981) and increases the stress on the sewer systems (Lindbeck, 1984; Shaw, 1994).

The experimental research outlined in this thesis shows that the permeable pavement increases the opportunity for infiltration and percolation. If rain water is allowed to infiltrate into the ground, a greater proportion of the input will reach the aeration zone and allow for groundwater recharge. Permeable pavements could reduce overland flow to zero by the infiltration of up to 100 mm of rainfall. If infiltration into the soil is not allowed, the structure can still reduce the volume of stormwater runoff by at least 30%, could attenuate the storm hydrograph and decrease the peak flow discharges significantly. Decreases in maximum flow volumes and the attenuation of stormwater runoff will decrease the volume of stormwater reaching the sewer system and reduce the risk of flooding in the urban environment downstream.

The overall impact on the fluvial system will also be significant. An increase in overland flow is known to create significant adjustments in the hydraulic geometry of river channels (Leopold and Maddock, 1953; Gregory and Park, 1976; Ferguson, 1987). Such changes could be minimised by improving infiltration and reducing the overland flow if permeable pavements are used as a source control technique. The problems of increased flow volumes and consequent increases in shear stresses which may induce sediment entrainment (Hellawell, 1986) in the fluvial system will also be alleviated.

Permeable pavements can control urban runoff by directly reducing the total volume of water entering the drainage system. The use of this plane infiltration approach is more advantageous in low traffic density areas than the use of permeable Macadam because the structure does not experience the same clogging disadvantages as seen in Sweden (Hogland *et al.*, 1987; Hogland, 1990), Japan (Fujita, 1993) or France (Raimbault, 1990), i.e., the surface has greater void openings than Macadam. Clogging of the permeable pavement could be argued to favourably increase the hydrological performance of the structure, allowing for greater retention and higher evaporation rates. The structure has the added advantage of being able to evaporate rainfall retained within the structure; again reducing the volume of water passing into the drainage system, producing a more "quasi-natural" hydrological cycle.

The degree to which permeable pavements control stormwater runoff depends on the structural design of the surface. The model discussed in Chapter 8 allows the engineer to design a structure for an individual site, i.e., if only 10% runoff is permitted, a greater depth of bedding material with a smaller grain size may be incorporated into the design. The engineer will have a design tool from which to predict the hydrological performance of the design structure without the need of extensive simulation experiments.

9.6.2 Control of the quality of urban runoff by using permeable pavements.

The urban environment concentrates populations and pollutants associated with anthropogenic activities. Sediment-associated pollutants can be four times greater in the urban environment than background levels in rural areas (Nriagu, 1979; Ellis and Revitt, 1982; Lord, 1987; Elliott and Pratt, 1989). Pollutant sources can be divided into two broad categories namely point and non-point pollution, with the latter being extremely difficult to monitor and control (Whipple, 1981; Loehr, 1984; Rutherford, 1988; Field and Pitt, 1990). A correlation between pollutant loads and the percentage area of impermeable surfaces in a catchment has been identified (Lindholm and Balmer, 1978). With an increase in pollutant loads on impermeable surfaces, stormwater runoff (which may entrain these pollutants) usually has a high concentration of pollutants which are released in a first flush. This produces a short sharp concentrated shock of pollutants reaching the receiving waters (Bradford, 1977; Lindholm and Balmer, 1978).

Detention devices (detaining stormwater runoff) can decrease pollutant loads and also the detrimental impact of this contamination receiving surface waters (Whipple, 1981; Mesuere and Fish, 1989; Cherrered and Chocat, 1990). Sediment-associated pollutants, e.g. heavy metals, can be reduced using these devices or by using a simple gravel matrix which allows filtration to occur (Aulenbach and Chan, 1988; Rajapakse and Ives, 1990). Since concentrations of heavy metals are high near roads and car parks (Johnston and Harrison, 1984; Lord, 1987; Yousef and Wanielista, 1986), and a gravel matrix can act as a filtration device, the use of permeable pavements may allow for sediment associated pollutants to be filtered and stored on-site. Just as the permeable pavement acts as an on-site source control for rainfall, it could perform a similar role for sediment-associated pollutants.

Diffuse sources of pollutants (non-point) in the urban environment may be stored in the permeable pavement which is essentially a passive system. In theory, stormwater runoff from roads could be directed onto these surfaces to allow for primary filtration of stormwater runoff. The permeable pavement structure could be specially designed to include layers of limestone which increases the pH and produces favourable conditions for heavy metal retention (Förstner and Wittman, 1983). The design can be altered depending on the site requirements and pollutant sources and types.

9.7 Recommendations for further research.

The next stage in the research into permeable pavement performance should examine the stability of heavy metals and other associated pollutants that could be filtered by the structure. The question then becomes "Is this structure to be a passive filtration system or could an active system be introduced which would absorb the pollutants making the structure act as a sink ?". With research in bio-remediation becoming more popular (Silverman et al., 1986; Silverman et al., 1988/89), could this structure be used as an area for on-site control in the urban environment ?.

Permeable pavements have been seen to control the quantity of urban runoff, thereby reducing the detrimental impacts of urbanisation. They have also been observed (Chapter 7) as being hydrologically efficient even after experiencing extreme sediment loadings. The maintenance requirements of these systems are low and the possibility of the structure to act as a sink for sediment associated pollutants is high.

APPENDIX A

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<u>APPENDIX B</u>

GLOSSARY LIST

POLLUTION. The introduction by man into the environment of substances or energy liable to cause hazards to human health, harm to living resources and ecological systems, damage to structures or amenity, or interference with legitimate uses of the environment. (Royal Commission on Environmental Pollution 1984)

RECURRENCE INTERVAL. The average period of time which a specific amount or intensity of rainfall can be expected to occur once. These data are of value in flood forecasting where the period of a particularly hazardous flood level can be expected at intervals, say, once in 25 years, or once in 50 years. This is not to say that the rainfall will appear at regular intervals, so that exact predictions of timing are impossible.

CHANNEL CAPACITY. The maximum volume of flow of a river within its' channel without overtopping its' bank.

HYDRAULIC GEOMETRY. An expression introduced in 1953 by L.B.Leopold and T.Maddock to describe the hydraulic characteristics of a stream channel. The mean velocity, the mean depth and the width of flowing water are the functions of discharge at a given river cross-section, since discharge is the product of the mean velocity and the cross-sectional area of flow. It has been shown that with increasing discharge the mean velocity, mean depth and width increase as power functions:$v=Kq^m$, $d=Cq^f$, $w=Aq^b$, where v is mean velocity, d is mean depth, w is width, Q is discharge and k,c,a,m,f and b are numerical coefficients. In addition to the three parameters of velocity, depth and width, the complete hydraulic geometry of a stream channel will include measurements of suspended-sediment load, gradient and bed roughness, all of which will affect the streams' capability of moving varying amounts of water and sediment.

FINES. Fine-grained soil or sediment is that which has more than 50% of its' bulk weight comprising particles smaller than 0.075 mm in diameter.

CHANNEL GEOMETRY. A term used in hydrology and in fluvial geomorphology to describe the spatial properties of a river channel. These include the width, depth, slope, gradient, bed roughness and wetted perimeter of the channel.

FLATNESS RATIO. This is measured by comparing the grain dimensions (a, b and c axis) and is calculated by
(A + B)/2C. The higher the value, the greater the grain resembles a disc. A minimum value of 1 represents an equi-dimensional particle.

RELATIVE HUMIDITY. This is the actual vapour pressure expressed as a percentage of the saturated vapour pressure at the same air temperature.

RETENTION: Retention is defined as the water held within the car park structure at a given time interval (units are given in mm unless otherwise stated).

TOTAL RETENTION: The total retention is defined as the amount of rainfall retained after monitoring on single event by the model car park structure. Retention after two hours (from the end of rainfall) was defined as the total retention because discharge from the model car park structure had ceased.

CUMULATIVE RETENTION: This includes total retention and the retention from previous rainfall events.

CUMULATIVE STORM RETENTION: This term refers to the measurements of the retention of rainfall during the rainfall event and up to the time when total retention is reached.

TOTAL DISCHARGE: The total discharge is defined as the discharge at two hours after rainfall has ceased. This denotes the time when no further discharge takes place and the base of the structure is sealed.

CUMULATIVE STORM DISCHARGE: This term refers to the measurements of the cumulative discharge during a rainfall event up to the time when total discharge has been reached.

LAG TIME: The lag time is defined as the time difference between the onset of rainfall and the start of discharge.

Mld: Mega litres per day.

AXIS: The A axis is the longest axis of a particle. The B axis is the breadth of a particle. The C axis is the depth of the particle.

REGRESSION ANALYSIS: A statistical technique which expresses the relationship between two or more variables in a graphic form. It comprises of fitting a regression line through a scatter of points in such a way that the sum of the squares of the distance between the points and the line is reduced to a minimum, i.e., the best fit is achieved. The analysis can be described in the form of an equation where $y = a + bx$, with y and x being the axis and y and x being constants.

APPENDIX C

Date May 1992	Box Number 1 Pea Gravel Diameter: 1-10mm Depth: 5cm Blocks: No	2 Pea Gravel Diameter: 1-10mm Depth: 5cm Blocks: Yes	3 Pea Gravel Diameter: 1-10mm Depth: 3cm Blocks: Yes	4 Pea Gravel Diameter: 1-10mm Depth: 7cm Blocks: Yes	5 Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	6 Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	7 Pea Gravel Diameter: 1-3mm Depth: 5cm Blocks: Yes	8 PG & Limestone Diameter: 5-10mm Depth: 5cm Blocks: Yes	9 PG & Limestone Diameter: 5-10mm Depth: 3cm/4cm Blocks: Yes	10 Limestone Diameter: 5-10mm Depth: 5cm Blocks: Yes
5 Rainfall (I) = Duration = Volume (I) = Code:	15 mm/h 1 hour 5.4 l B1R155									
6 Rainfall (I) = Duration = Volume (I) = Code:		15 mm/h 1 hour 5.4 l B2R165								
21 Rainfall (I) = Duration = Volume (I) = Code:			15mm/h 1 hour 5.4 l B3R1215							
22 Rainfall (I) = Duration = Volume (I) = Code:				15mm/h 1 hour 5.4 l B4R1225						
23 Rainfall (I) = Duration = Volume (I) = Code:					15mm/h 1 hour 5.4 l B5R1235					
24 Rainfall (I) = Duration = Volume (I) = Code:						15mm/h 1 hour 5.4 l B6R1245				
25 Rainfall (I) = Duration = Volume (I) = Code:							15mm/h 1 hour 5.4 l B7R1255			
26 Rainfall (I) = Duration = Volume (I) = Code:								15mm/h 1 hour 5.4 l B8R1265		
27 Rainfall (I) = Duration = Volume (I) = Code:									15mm/h 1 hour 5.4 l B9R1275	
28 Rainfall (I) = Duration = Volume (I) = Code:										15mm/h 1 hour 5.4 l B10R1285

Date May 1992	Box Number 1 Pea Gravel Diameter: 1-10mm Depth: 5cm Blocks: No	2 Pea Gravel Diameter: 1-10mm Depth: 5cm Blocks: Yes	3 Pea Gravel Diameter: 1-10mm Depth: 3cm Blocks: Yes	4 Pea Gravel Diameter: 1-10mm Depth: 7cm Blocks: Yes	5 Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	6 Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	7 Pea Gravel Diameter: 1-3mm Depth: 5cm Blocks: Yes	8 PG & Limestone Diameter: 5-10mm Depth: 5cm Blocks: Yes	9 PG & Limestone Diameter: 5-10mm Depth: 3cm/4cm Blocks: Yes	10 Limestone Diameter: 5-10mm Depth: 5cm Blocks: Yes
29 Rainfall (l) = Duration = Volume (l) = Code:										30mm/h 0.5 hour 5.518 l B10R2296

Date June 1992	Box Number 1	2	3	4	5	6	7	8	9	10
	Pea Gravel Diameter: 1-10mm Depth: 5cm Blocks: No	Pea Gravel Diameter: 1-10mm Depth: 5cm Blocks: Yes	Pea Gravel Diameter: 1-10mm Depth: 3cm Blocks: Yes	Pea Gravel Diameter: 1-10mm Depth: 7cm Blocks: Yes	Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	Pea Gravel Diameter: 1-3mm Depth: 5cm Blocks: Yes	PG & Limestone Diameter: 5-10mm Depth: 5cm Blocks: Yes	PG & Limestone Diameter: 5-10mm Depth: 3cm/4cm Blocks: Yes	Limestone Diameter: 5-10mm Depth: 5cm Blocks: Yes
18 Rainfall (l) = Duration = Volume (l) = Code:	30mm/h 0.5 hour 5.4 l B1R2186									
19 Rainfall (l) = Duration = Volume (l) = Code:		30mm/h 0.5 hour 5.433 l B2R2196								
20 Rainfall (l) = Duration = Volume (l) = Code:			30mm/h 0.5 hour 5.4 l B3R2206							
21 Rainfall (l) = Duration = Volume (l) = Code:				5.45mm/h 0.33hour 0.645 l B4R2216						
22 Rainfall (l) = Duration = Volume (l) = Code:				30mm/h 0.5 hour 5.4 l B4R3226						
23 Rainfall (l) = Duration = Volume (l) = Code:					30mm/h 0.5 hour 5.4 l B5R2236					
24 Rainfall (l) = Duration = Volume (l) = Code:						30mm/h 0.5 hour 5.4 l B6R2246				
26 Rainfall (l) = Duration = Volume (l) = Code:							30mm/h 0.5 hour 5.539 l B7R2266			
27 Rainfall (l) = Duration = Volume (l) = Code:								30mm/h 0.5 hour 5.569 l B8R2276		
28 Rainfall (l) = Duration = Volume (l) = Code:									30mm/h 0.5 hour 5.614 l B9R2286	

Date July 1992	Box Number 1	2	3	4	5	6	7	8	9	10
	Pea Gravel Diameter: 1-10mm Depth: 5cm Blocks: No	Pea Gravel Diameter: 1-10mm Depth: 5cm Blocks: Yes	Pea Gravel Diameter: 1-10mm Depth: 3cm Blocks: Yes	Pea Gravel Diameter: 1-10mm Depth: 7cm Blocks: Yes	Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	Pea Gravel Diameter: 1-3mm Depth: 5cm Blocks: Yes	PG & Limestone Diameter: 5-10mm Depth: 5cm Blocks: Yes	PG & Limestone Diameter: 5-10mm Depth: 3cm/4cm Blocks: Yes	Limestone Diameter: 5-10mm Depth: 5cm Blocks: Yes
1 Rainfall (i) = Duration = Volume (l) = Code:	7.5mm/h 2 hour 5.4 l B1R317									
2 Rainfall (i) = Duration = Volume (l) = Code:		7.5mm/h 2 hour 5.4 l B2R327								
3 Rainfall (i) = Duration = Volume (l) = Code:			7.5mm/h 2 hour 5.4 l B3R337							
4 Rainfall (i) = Duration = Volume (l) = Code:				7.5mm/h 2 hour 5.464 l B4R447						
5 Rainfall (i) = Duration = Volume (l) = Code:					7.5mm/h 2 hour 5.409 l B5R357					
6 Rainfall (i) = Duration = Volume (l) = Code:						7.5mm/h 2 hour 5.411 l B6R367				
7 Rainfall (i) = Duration = Volume (l) = Code:							7.5mm/h 2 hour 5.4 l B7R377			
9 Rainfall (i) = Duration = Volume (l) = Code:								7.5mm/h 2 hour 5.4 l B8R397		
10 Rainfall (i) = Duration = Volume (l) = Code:									7.5mm/h 2 hour 5.465 l B9R3107	
11 Rainfall (i) = Duration = Volume (l) = Code:										7.5mm/h 2 hour 5.414 l B10R31177

Date July 1992	Box Number 1 Pea Gravel Diameter: 1-10mm Depth: 5cm Blocks: No	2 Pea Gravel Diameter: 1-10mm Depth: 5cm Blocks: Yes	3 Pea Gravel Diameter: 1-10mm Depth: 3cm Blocks: Yes	4 Pea Gravel Diameter: 1-10mm Depth: 7cm Blocks: Yes	5 Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	6 Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	7 Pea Gravel Diameter: 1-3mm Depth: 5cm Blocks: Yes	8 PG & Limestone Diameter: 5-10mm Depth: 5cm Blocks: Yes	9 PG & Limestone Diameter: 5-10mm Depth: 3cm/4cm Blocks: Yes	10 Limestone Diameter: 5-10mm Depth: 5cm Blocks: Yes
18 Rainfall (l) = Duration = Volume (l) = Code:	10 5 hour 18 l B1R4187 BOX 1 EXPERIMENT COMPLETED BOX COMPONENTS CHANGED									30mm/h 0.5 hour 5.518 l B10R2296

Date August 1992	Box Number 1 Blocks Only	2 Pea Gravel Diameter: 1-10mm Depth: 5cm Blocks: Yes	3 Pea Gravel Diameter: 1-10mm Depth: 3cm Blocks: Yes	4 Pea Gravel Diameter: 1-10mm Depth: 7cm Blocks: Yes	5 Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	6 Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	7 Pea Gravel Diameter: 1-3mm Depth: 5cm Blocks: Yes	8 PG & Limestone Diameter: 5-10mm Depth: 5cm Blocks: Yes	9 PG & Limestone Diameter: 5-10mm Depth: 3cm/4cm Blocks: Yes	10 Limestone Diameter: 5-10mm Depth: 5cm Blocks: Yes
4 Rainfall (i) = Duration = Volume (l) = Code:	30mm/h 0.5 hour 6.4 l BLOCK148									
5 Rainfall (i) = Duration = Volume (l) = Code:	15mm/h 1 hour 6.4 l BLOCK258	5.8mm/h 5 hour 10.5 l B2R458								
6 Rainfall (i) = Duration = Volume (l) = Code:	7.5mm/h 2 hour 6.4 l BLOCK368		9.26mm/h 3 hour 10 l B3R468							
7 Rainfall (i) = Duration = Volume (l) = Code:				9.26mm/h 3 hour 10 l B4R578	9.26mm/h 3 hour 10 l B5R478					
10 Rainfall (i) = Duration = Volume (l) = Code:						9.26mm/h 3 hour 10 l B6R4108				
11 Rainfall (i) = Duration = Volume (l) = Code:							9.26mm/h 3 hour 10 l B7R4118	9.26mm/h 3 hour 10 l B8R4118		
13 Rainfall (i) = Duration = Volume (l) = Code:									9.26mm/h 3 hour 10 l B9R4138	9.26mm/h 3 hour 10 l B10R4138
	Experiment continues until 29 October	Experiment finished 21 September	Experiment finished 21 September	Experiment finished 21 September	Experiment finished 21 September	Experiment finished 21 September	Experiment finished 21 September	Experiment finished 21 September	Experiment finished 21 September	Experiment finished 21 September

Date October 1992	Box Number 1 Blocks Only	2 Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	3 Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	4 Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	5 Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	6 Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	7 Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	8 Pea Gravel 50% size 3-5mm 50% size 5-10mm Depth: 5cm Blocks: Yes	9 Pea Gravel 50% size 3-5mm 50% size 5-10mm Depth: 3cm/4cm Blocks: Yes	10 Pea Gravel 50% size 3-5mm 50% size 5-10mm Depth: 5cm Blocks: Yes
9 Rainfall (l) = Duration = Volume (l) = Code:	15mm/h 1 hour 5.4 l BLOCK4910									
10 Rainfall (l) = Duration = Volume (l) = Code:	15mm/h 1 hour 5.477 l BLOCK51010									
11 Rainfall (l) = Duration = Volume (l) = Code:	15mm/h 1 hour 5.407 l BLOCK61110									
12 Rainfall (l) = Duration = Volume (l) = Code:	15mm/h 1 hour 5.4 l BLOCK71210									
19 Rainfall (l) = Duration = Volume (l) = Code: Additions Type Amount (g)	15mm/h 1 hour 5.517 l BLOCK81910	15mm/h 1 hour 5.440 l B2R1910 Yes Clay 18.25 g	15mm/h 1 hour 5.428 l B3R1910 Yes Clay/Peat 18.2 g	15mm/h 1 hour 5.418 l B4R1910 No	15mm/h 1 hour 5.422 l B5R1910 Yes Clay 18.25 g	15mm/h 1 hour 5.402 l B6R1910 Yes Clay/Peat 18.2 g	15mm/h 1 hour 5.409 l B7R1910 No	15mm/h 1 hour 5.409 l B8R1910 Yes Clay 18.25 g	15mm/h 1 hour 5.400 l B9R1910 Yes Clay/Peat 18.2 g	15mm/h 1 hour 5.630 l B10R1910 No
20 Rainfall (l) = Duration = Volume (l) = Code: Additions Type Amount (g)	15mm/h 1 hour 5.44 l BLOCK92010	15mm/h 1 hour 5.418 l B2R2010 Yes Clay 18.25 g	15mm/h 1 hour 5.540 l B3R2010 Yes Clay/Peat 18.2 g	15mm/h 1 hour 5.424 l B4R2010 No	15mm/h 1 hour 5.419 l B5R2010 Yes Clay 18.25 g	15mm/h 1 hour 5.424 l B6R2010 Yes Clay/Peat 18.2 g	15mm/h 1 hour 5.442 l B7R2010 No	15mm/h 1 hour 5.434 l B8R2010 Yes Clay 18.25 g	15mm/h 1 hour 5.400 l B9R2010 Yes Clay/Peat 18.2 g	15mm/h 1 hour 5.435 l B10R2010 No
22 Rainfall (l) = Duration = Volume (l) = Code: Additions Type Amount (g)	15mm/h 1 hour 5.41 l BLOCK102210	15mm/h 1 hour 5.396 l B2R2210 Yes Clay 18.25 g	15mm/h 1 hour 5.409 l B3R2210 Yes Clay/Peat 18.2 g	15mm/h 1 hour 5.447 l B4R2210 No	15mm/h 1 hour 5.445 l B5R2210 Yes Clay 18.25 g	15mm/h 1 hour 5.405 l B6R2210 Yes Clay/Peat 18.2 g	15mm/h 1 hour 5.477 l B7R2210 No	15mm/h 1 hour 5.452 l B8R2210 Yes Clay 18.25 g	15mm/h 1 hour 5.574 l B9R2210 Yes Clay/Peat 18.2 g	15mm/h 1 hour 5.400 l B10R2210 No

Date October 1992	Box Number 1	2	3	4	5	6	7	8	9	10
	Blocks Only	Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	Pea Gravel 50% size 3-5mm 50% size 5-10mm Depth: 5cm Blocks: Yes	Pea Gravel 50% size 3-5mm 50% size 5-10mm Depth: 3cm/4cm Blocks: Yes	Pea Gravel 50% size 3-5mm 50% size 5-10mm Depth: 5cm Blocks: Yes
26										
Rainfall (i) =	15mm/h	15mm/h	15mm/h	15mm/h	15mm/h	15mm/h	15mm/h	15mm/h	15mm/h	15mm/h
Duration =	1 hour	1 hour	1 hour	1 hour	1 hour	1 hour	1 hour	1 hour	1 hour	1 hour
Volume (l) =	5.406 l	5.405 l	5.417 l	5.350 l	5.427 l	5.472 l	5.484 l	5.448 l	5.500 l	5.460 l
Code:	BLOCK112510	B2R2510	B3R2510	B4R2510	B5R2510	B6R2510	B7R2510	B8R2510	B9R2510	B10R2510
Additions		Yes	Yes	No	Yes	Yes	No	Yes	Yes	No
Type		Clay	Clay/Peat		Clay	Clay/Peat		Clay	Clay/Peat	
Amount (g)		18.25 g	18.2 g		18.25 g	18.2 g		18.25 g	18.2 g	
29										
Rainfall (i) =	15mm/h	15mm/h	15mm/h	15mm/h	15mm/h	15mm/h	15mm/h	15mm/h	15mm/h	15mm/h
Duration =	1 hour	1 hour	1 hour	1 hour	1 hour	1 hour	1 hour	1 hour	1 hour	1 hour
Volume (l) =	5.503 l	5.460 l	5.980 l	5.400 l	5.440 l	5.440 l	5.445 l	5.440 l	5.440 l	5.498 l
Code:	BLOCK122910	B2R2910	B3R2910	B4R2910	B5R2910	B6R2910	B7R2910	B8R2910	B9R2910	B10R2910
Additions		Yes	Yes	No	Yes	Yes	No	Yes	Yes	No
Type		Clay	Clay/Peat		Clay	Clay/Peat		Clay	Clay/Peat	
Amount (g)		18.25 g	18.2 g		18.25 g	18.2 g		18.25 g	18.2 g	
31										
Rainfall (i) =		15mm/h	15mm/h	15mm/h	15mm/h	15mm/h	15mm/h	15mm/h	15mm/h	15mm/h
Duration =		1 hour	1 hour	1 hour	1 hour	1 hour	1 hour	1 hour	1 hour	1 hour
Volume (l) =		5.433 l	5.454 l	5.540 l	5.444 l	5.450 l	5.450 l	5.450 l	5.430 l	5.700 l
Code:		B2R3110	B3R3110	B4R3110	B5R3110	B6R3110	B7R3110	B8R3110	B9R3110	B10R3110
Additions		Yes	Yes	No	Yes	Yes	No	Yes	Yes	No
Type		Clay	Clay/Peat		Clay	Clay/Peat		Clay	Clay/Peat	
Amount (g)		91.25 g	91.25 g		91.25 g	91.25 g		91.25 g	91.25 g	
	Experiment finished 2 November	Experiment continues	Experiment continues	Experiment continues	Experiment continues	Experiment continues	Experiment continues	Experiment continues	Experiment continues	Experiment continues

Date November 1992	Box Number 1	2	3	4	5	6	7	8	9	10
	Blocks Only	Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	Pea Gravel 50% size 3-5mm 50% size 5-10mm Depth: 5cm Blocks: Yes	Pea Gravel 50% size 3-5mm 50% size 5-10mm Depth: 3cm/4cm Blocks: Yes	Pea Gravel 50% size 3-5mm 50% size 5-10mm Depth: 5cm Blocks: Yes
2 Rainfall (l) = Duration = Volume (l) = Code: Additions Type Amount (g)		15mm/h 1 hour 5.420 l B2R211 Yes Clay 91.25 g	15mm/h 1 hour 5.445 l B3R211 Yes Clay/Peat 91.25 g	15mm/h 1 hour 5.862 l B4R211 No	15mm/h 1 hour 5.570 l B5R211 Yes Clay 91.25 g	15mm/h 1 hour 5.426 l B6R211 Yes Clay/Peat 91.25 g	15mm/h 1 hour 5.625 l B7R211 No	15mm/h 1 hour 5.436 B8R211 Yes Clay 91.25 g	15mm/h 1 hour 5.419 l B9R211 Yes Clay/Peat 91.25 g	15mm/h 1 hour 5.514 l B10R211 No
6 Rainfall (l) = Duration = Volume (l) = Code: Additions Type Amount (g)		15mm/h 1 hour 5.555 l B2R511 Yes Clay 91.25 g	15mm/h 1 hour 5.438 l B3R511 Yes Clay/Peat 91.25 g	15mm/h 1 hour 5.385 l B4R511 No	15mm/h 1 hour 5.385 l B5R511 Yes Clay 91.25 g	15mm/h 1 hour 5.405 l B6R511 Yes Clay/Peat 91.25 g	15mm/h 1 hour 5.800 l B7R511 No	15mm/h 1 hour 5.400 l B8R511 Yes Clay 91.25 g	15mm/h 1 hour 5.479 l B9R511 Yes Clay/Peat 91.25 g	15mm/h 1 hour 5.455 l B10R511 No
9 Rainfall (l) = Duration = Volume (l) = Code: Additions Type Amount (g)		15mm/h 1 hour 5.800 l B2R911 No	15mm/h 1 hour 5.534 l B3R911 No	15mm/h 1 hour 5.600 l B4R911 No	15mm/h 1 hour 5.538 l B5R911 No	15mm/h 1 hour 5.500 l B6R911 No	15mm/h 1 hour 5.420 l B7R911 No	15mm/h 1 hour 5.409 l B8R911 No	15mm/h 1 hour 5.430 l B9R911 No	15mm/h 1 hour 5.510 l B10R911 No
11 Rainfall (l) = Duration = Volume (l) = Code: Additions Type Amount (g)		15mm/h 1 hour 5.424 l B2R1111 No	15mm/h 1 hour 5.402 l B3R1111 No	15mm/h 1 hour 5.420 l B4R1111 No	15mm/h 1 hour 5.420 l B5R1111 No	15mm/h 1 hour 5.420 l B6R1111 No	15mm/h 1 hour 5.425 l B7R1111 No	15mm/h 1 hour 5.410 l B8R1111 No	15mm/h 1 hour 5.850 l B9R1111 No	15mm/h 1 hour 5.490 l B10R1111 No
13 Rainfall (l) = Duration = Volume (l) = Code: Additions Type Amount (g)		15mm/h 1 hour 5.783 l B2R1311 No	15mm/h 1 hour 6.130 l B3R1311 No	15mm/h 1 hour 5.400 l B4R1311 No	15mm/h 1 hour 5.410 l B5R1311 No	15mm/h 1 hour 5.400 l B6R1311 No	15mm/h 1 hour 5.400 l B7R1311 No	15mm/h 1 hour 5.400 l B8R1311 No	15mm/h 1 hour 6.652 l B9R1311 No	15mm/h 1 hour 5.406 l B10R1311 No
15 Rainfall (l) = Duration = Volume (l) = Code: Additions Type Amount (g)		15mm/h 1 hour 5.407 l B2R1511 No	15mm/h 1 hour 5.400 l B3R1511 No	15mm/h 1 hour 5.408 l B4R1511 No	15mm/h 1 hour 5.413 l B5R1511 No	15mm/h 1 hour 5.430 l B6R1511 No	15mm/h 1 hour 5.430 l B7R1511 No	15mm/h 1 hour 5.700 l B8R1511 No	15mm/h 1 hour 5.406 l B9R1511 No	15mm/h 1 hour 5.414 l B10R1511 No

Date November 1992	Box Number 1 Blocks Only	2 Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	3 Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	4 Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	5 Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	6 Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	7 Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	8 Pea Gravel 50% size 3-5mm 50% size 5-10mm Depth: 5cm Blocks: Yes	9 Pea Gravel 50% size 3-5mm 50% size 5-10mm Depth: 3cm/4cm Blocks: Yes	10 Pea Gravel 50% size 3-5mm 50% size 5-10mm Depth: 5cm Blocks: Yes
17 Duration= Volume (l)= Code: Additions Type Amount (g)		1 hour 5.408 l B2R1711 No Experiment continues	1 hour 5.400 l B3R1711 No Experiment continues	1 hour 5.402 l B4R1711 No Experiment continues	1 hour 5.402 l B5R1711 No Experiment completed 7 December	1 hour 5.405 l B6R1711 No Experiment completed 7 December	1 hour 5.411 l B7R1711 No Experiment completed 7 December	1 hour 5.400 l B8R1711 No Experiment completed 7 December	1 hour 5.406 l B9R1711 No Experiment completed 7 December	1 hour 5.436 l B10R1711 No Experiment completed 7 December

Date January 1992	Box Number 1 Blocks Only	2 Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	3 Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	4 Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	5 Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	6 Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	7 Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	8 Pea Gravel 50% size 3-5mm 50% size 5-10mm Depth: 5cm Blocks: Yes	9 Pea Gravel 50% size 3-5mm 50% size 5-10mm Depth: 3cm/4cm Blocks: Yes	10 Pea Gravel 50% size 3-5mm 50% size 5-10mm Depth: 5cm Blocks: Yes
11										
Rainfall (l) =		15mm/h	15mm/h	15mm/h						
Duration =		1 hour	1 hour	1 hour						
Volume (l) =		5.506 l	5.412 l	5.500 l						
Code:		B2R111	B3R111	B4R111						
Additions		Yes	Yes	Yes						
Type		Sand	Sand	Sand						
Amount (g)		270.6 g	270.6 g	270.6 g						
12										
Rainfall (l) =		15mm/h	15mm/h	15mm/h						
Duration =		1 hour	1 hour	1 hour						
Volume (l) =		5.442 l	5.404 l	5.501 l						
Code:		B2R121	B3R121	B4R121						
Additions		No	No	No						
Type										
Amount (g)										
13										
Rainfall (l) =		15mm/h	15mm/h	15mm/h						
Duration =		1 hour	1 hour	1 hour						
Volume (l) =		5.545 l	5.412 l	5.430 l						
Code:		B2R131	B3R131	B4R131						
Additions		Yes	Yes	Yes						
Type		Sand	Sand	Sand						
Amount (g)		270.6 g	270.6 g	270.6 g						
14										
Rainfall (l) =		15mm/h	15mm/h	15mm/h						
Duration =		1 hour	1 hour	1 hour						
Volume (l) =		5.465 l	5400 l	5.480 l						
Code:		B2R141	B3R141	B4R141						
Additions		No	No	No						
Type										
Amount (g)										
15										
Rainfall (l) =		15mm/h	15mm/h	15mm/h						
Duration =		1 hour	1 hour	1 hour						
Volume (l) =		5.434 l	5530 l	5.410 l						
Code:		B2R151	B3R151	B4R151						
Additions		Yes	Yes	Yes						
Type		Sand	Sand	Sand						
Amount (g)		270.6 g	270.6 g	270.6 g						
18										
Rainfall (l) =		15mm/h	15mm/h	15mm/h						
Duration =		1 hour	1 hour	1 hour						
Volume (l) =		5.556 l	5.430 l	5.420 l						
Code:		B2R181	B3R181	B4R181						
Additions		No	No	No						
Type										
Amount (g)										

Date January 1992	Box Number 1	2	3	4	5	6	7	8	9	10
	Blocks Only	Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	Pea Gravel 50% size 3-5mm 50% size 5-10mm Depth: 5cm Blocks: Yes	Pea Gravel 50% size 3-5mm 50% size 5-10mm Depth: 3cm/4cm Blocks: Yes	Pea Gravel 50% size 3-5mm 50% size 5-10mm Depth: 5cm Blocks: Yes
19										
Rainfall (i) =		15mm/h	15mm/h	15mm/h						
Duration =		1 hour	1 hour	1 hour						
Volume (l) =		5.534 l	5.400 l	5.480 l						
Code:		B2R191	B3R191	B4R191						
Additions		Yes	Yes	Yes						
Type		Sand	Sand	Sand						
Amount (g)		270.6 g	270.6 g	270.6 g						
20										
Rainfall (i) =		15mm/h	15mm/h	15mm/h						
Duration =		1 hour	1 hour	1 hour						
Volume (l) =		5.440 l	5.536 l	5.472 l						
Code:		B2R201	B3R201	B4R201						
Additions		No	No	No						
Type										
Amount (g)										
21										
Rainfall (i) =		15mm/h	15mm/h	15mm/h						
Duration =		1 hour	1 hour	1 hour						
Volume (l) =		5.449 l	5.541 l	5.490 l						
Code:		B2R211	B3R211	B4R211						
Additions		Yes	Yes	Yes						
Type		Sand	Sand	Sand						
Amount (g)		270.6 g	270.6 g	270.6 g						
22										
Rainfall (i) =		15mm/h	15mm/h	15mm/h						
Duration =		1 hour	1 hour	1 hour						
Volume (l) =		5.420 l	5.410 l	5.455 l						
Code:		B2R221	B3R221	B4R221						
Additions		No	No	No						
Type										
Amount (g)										
23										
Rainfall (i) =		15mm/h	15mm/h	15mm/h						
Duration =		1 hour	1 hour	1 hour						
Volume (l) =		5.440 l	5.440 l	5.465 l						
Code:		B2R231	B3R231	B4R231						
Additions		Yes	Yes	Yes						
Type		Sand	Sand	Sand						
Amount (g)		270.6 g	270.6 g	270.6 g						
24										
Rainfall (i) =		15mm/h	15mm/h	15mm/h						
Duration =		1 hour	1 hour	1 hour						
Volume (l) =		5.440 l	5.400 l	5.500 l						
Code:		B2R241	B3R241	B4R241						
Additions		No	No	No						
Type										
Amount (g)										

Date January 1992	Box Number 1 Blocks Only	2 Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	3 Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	4 Pea Gravel Diameter: 5-10mm Depth: 5cm Blocks: Yes	5 Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	6 Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	7 Pea Gravel Diameter: 3-5mm Depth: 5cm Blocks: Yes	8 Pea Gravel 50% size 3-5mm 50% size 5-10mm Depth: 5cm Blocks: Yes	9 Pea Gravel 50% size 3-5mm 50% size 5-10mm Depth: 3cm/4cm Blocks: Yes	10 Pea Gravel 50% size 3-5mm 50% size 5-10mm Depth: 5cm Blocks: Yes
25										
Rainfall (I) =		15mm/h	15mm/h	15mm/h						
Duration =		1 hour	1 hour	1 hour						
Volume (I) =		5.450 l	5.510 l	5.844 l						
Code:		B2R251	B3R251	B4R251						
Additions		Yes	Yes	Yes						
Type		Sand	Sand	Sand						
Amount (g)		270.6 g	270.6 g	270.6 g						
27										
Rainfall (I) =		4.89mm/h								
Duration =		0.5 hour								
Volume (I) =		0.880 l								
Code:		B2R241								
Additions		No								
Type										
Amount (g)										
30										
Rainfall (I) =		15mm/h	15mm/h	15mm/h						
Duration =		1 hour	1 hour	1 hour						
Volume (I) =		5.405 l	5.482 l	5.680 l						
Code:		B2R301	B3R301	B4R301						
Additions		No	No	No						
Type										
Amount (g)										
February 1										
Rainfall (I) =		15mm/h	15mm/h	15mm/h						
Duration =		1 hour	1 hour	1 hour						
Volume (I) =		5.640 l	5.690 l	5.643 l						
Code:		B2R12	B3R12	B4R12						
Additions		No	No	No						
Type										
Amount (g)										
2										
Rainfall (I) =		15mm/h	15mm/h	15mm/h						
Duration =		1 hour	1 hour	1 hour						
Volume (I) =		5.470 l	5.700 l	5.500 l						
Code:		B2R22	B3R22	B4R22						
Additions		No	No	No						
Type										
Amount (g)										
3										
Rainfall (I) =		15mm/h	15mm/h	15mm/h						
Duration =		1 hour	1 hour	1 hour						
Volume (I) =		5.600 l	5.480 l	5.450 l						
Code:		B2R32	B3R32	B4R32						
Additions		No	No	No						
Type										
Amount (g)										

Date February 1992	Box Number 1	2	3	4	5	6	7	8	9	10
	Blocks Only	**Pea Gravel** **Diameter:** 5-10mm **Depth:** 5cm **Blocks:** Yes	**Pea Gravel** **Diameter:** 5-10mm **Depth:** 5cm **Blocks:** Yes	**Pea Gravel** **Diameter:** 5-10mm **Depth:** 5cm **Blocks:** Yes	***Pea Gravel*** **Diameter:** 3-5mm **Depth:** 5cm **Blocks:** Yes	***Pea Gravel*** **Diameter:** 3-5mm **Depth:** 5cm **Blocks:** Yes	***Pea Gravel*** **Diameter:** 3-5mm **Depth:** 5cm **Blocks:** Yes	**Pea Gravel** **50% size** 3-5mm **50% size** 5-10mm **Depth:** 5cm **Blocks:** Yes	**Pea Gravel** **50% size** 3-5mm **50% size** 5-10mm **Depth:** 3cm/4cm **Blocks:** Yes	**Pea Gravel** **50% size** 3-5mm **50% size** 5-10mm **Depth:** 5cm **Blocks:** Yes
4 **Rainfall (l) =** **Duration =** **Volume (l) =** **Code:** **Additions** **Type** **Amount (g)**		15mm/h 1 hour 6.142 l B2R43 No Experiment Finished	15mm/h 1 hour 5.460 l B3R43 No Experiment Finished	15mm/h 1 hour 6.135 l B4R43 No Experiment Finished						

APPENDIX D

LISTING OF COMPUTER PROGRAMMES

Programme for the thermocouples using the PC208 software.

```
------------------------------------------------------
Program:
Flag Usage:
Input channel Usage:
Excitation Channel Usage:
Continuous Analog Output Usage:
Control Port Usage:
Pulse Input Channel Usage:
Output Array Definitions:

*       1               TABLE 1 PROGRAMS
 01:0.0000     SEC.EXECUTION INTERVAL

0.1:  P        END TABLE 1


*       2               TABLE 2 PROGRAMS
 01:0.0000     SEC.EXECUTION INTERVAL

0.1:  P        END TABLE 2


*       3               TABLE 3 PROGRAMS
0.1:  P        END TABLE 1


*  4           MODE 4 OUTPUT OPTIONS
 01:00         TAPE/PRINTER OPTION
 02:00         PRINTER BAUD OPTION


*  A           MODE 10 MEMORY ALLOCATION
 01:28         INPUT LOCATIONS
 02:64         INTERMEDIATE LOCATIONS


*  C           MODE 12 SECURITY (OSX-O)
 01:00         SECURITY OPTION
 02:0000               SECURITY CODE
```

Programme for Balances and RH probes using PC208 software

Program:
Flag Usage:
Input channel Usage:
Excitation Channel Usage:
Control Port Usage:
Pulse Input Channel Usage:
Output Array Definitions:

```
*       1            TABLE 1 PROGRAMS
 01: 0.5             SEC.EXECUTION INTERVAL

01:  P91             IF FLAG/PORT
 01: 11              DO IF FLAG 1 IS HIGH
 02: 0       GO TO END OF PROGRAM TABLE

02:  P32             Z=Z+1
 01: 5       Z LOC :

03:  P86             DO
 01: 10              SET HIGH FLAG 0 (OUTPUT)

04:  P87             BEGINNING OF LOOP
 01: 60              DELAY
 02: 240             LOOP COUNT

05:  P86             DO
 01: 1       CALL SUBROUTINE 1

06:  P89             IF X<=>F
 01: 5       X LOC
 02: 3       >=
 03: 2880    F
 04: 31              EXIT LOOP IS TRUE

07:  P95             END

08:  P86             DO
 01: 10              SET HIGH FLAG 0 (OUTPUT)

09:  P87             BEGINNING OF LOOP
 01: 600             DELAY
 02: 12              LOOP COUNT

10:  P86             DO
 01: 1       CALL SUBROUTINE 1
```

```
11:  P89            IF X<=>F
 01: 5         X LOC
 02: 3         >=
 03: 4320      F
 04: 31             EXIT LOOP IF TRUE

12:  P95            END

13:  P87            BEGINNING OF LOOP
 01: 7200      DELAY
 02: 0         LOOP COUNT

14:  P86            DO
 01: 1         CALL SUBROUTINE 1

15:  P95            END

16:  P         END TABLE 1


*   2          TABLE 2 PROGRAMS
 01: 0.0000    SEC. EXECUTION INTERVAL

01:  P         END TABLE 2

*   3          TABLE 3 SUBROUTINES

01:  P85            BEGINNING OF SUBROUTINE
 01: 1         SUBROUTINE NUMBER

02:  P30            Z=F
 01: 209            F
 02: 0         EXPONENT OF 10
 03: 1         Z LOC (:CMD.Q)

03:  P30            Z=F
 01: 141            F
 02: 0         EXPONENT OF 10
 03: 2         Z LOC (CAR.RET.)

04:  P15            USER SPECIAL
 01: 01
 02: 01
 03: 10
 04: 1
 05: 1
```

06: 2
07: 13
08: 17
09: 300
10: 03
11: 1
12: 0

05: P15 USER SPECIAL
01: 01 1
02: 01
03: 10
04: 4
05: 1
06: 2
07: 13
08: 17
09: 300
10: 04
11: 01
12: 0

06: P86 DO
01: 10 SET HIGH FLAG 0 (OUTPUT)

07: P77 REAL TIME
01: 111 DAY, HOUR-MINUTE, SECONDS

08: P70 SAMPLE
01: 2 REPS
02: 3 LOC

09: P95 END

10: P END TABLE 3

* A MODE 10 MEMORY ALLOCATION
01: 28 INPUT LOCATIONS
02: 64 INTERMEDIATE LOCATIONS
03: 768 FINAL STORAGE AREA 2

* C MODE 12 SECURITY
01: 0000 LOCK 1
02: 0000 LOCK 2
03: 0000 LOCK 3

PROGRAMME FOR CALCULATION MODEL BOX HYDROLOGICAL RESPONSE. WRITTEN IN QBASIC.

```
REM  PROGRAM CALLED MODEL.BAS
CLS
PRINT : PRINT : PRINT : PRINT : PRINT "  THIS PROGRAMME MODELS THE
RAINFALL, RETENTION AND DISCHARGE CHARACTERISTICS"
      PRINT :
      PRINT "           EXHIBITED BY A MODEL PERMEABLE PAVEMENT
STRUCTURE"
      PRINT : PRINT : PRINT : PRINT
      PRINT "                    COPYRIGHT TOFF BERRY 1995"
      PRINT : PRINT : PRINT : PRINT : PRINT : PRINT "                      PRESS
ANY KEY"

   COLOR 7, 0
   A$ = "?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?"
   WHILE INKEY$ <> "": WEND 'CLEAR KEYBOARD BUFFER

   WHILE INKEY$ = ""
     FOR A = 1 TO 5
       LOCATE 1, 1                  'PRINT HORIZONTAL SPARKLES
       PRINT MID$(A$, A, 80);
       LOCATE 22, 1
       PRINT MID$(A$, 6 - A, 80);

       FOR B = 2 TO 21              'PRINT VERTICAL SPARKLES
         C = (A + B) MOD 5
         IF C = 1 THEN
           LOCATE B, 80
           PRINT "!";
           LOCATE 23 - B, 1
           PRINT CHR$(173)
           ELSE
           LOCATE B, 80
           PRINT " ";
           LOCATE 23 - B, 1
           PRINT " ";
         END IF
       NEXT B
     NEXT A
   WEND
REM***********************SECTION
ONE*************************************************
1 CLS
```

```
2 PRINT
"=============================================================================="
3 PRINT "                    DATA INPUT SEQUENCE"
4 PRINT
"=============================================================================="
5 PRINT : PRINT : PRINT :
INPUT "BOX NUMBER"; BOX
INPUT "ENTER NUMBER OF RAINFALL EVENTS TO BE CALCULATED"; E
IF E < 1 AND E > 5 THEN GOTO 5
20 INPUT "ENTER DEPTH OF RAINFALL REACHING SURFACE DURING
EVENT 1 (MM)= "; RAINS
30 INPUT "DURATION OF RAINFALL EVENT (HOURS,MINS)= "; HOURS, MINS:
31 FR = MINS + (HOURS * 60): REM TIME CONVERTED TO MINUTES
33 DURAT = FR / 60
36 INTENSITY = (RAINS / (FR / 60))
50 INPUT "AREA OF SURFACE (M2)"; BEDAREA
55 RAING = (BEDAREA * RAINS) * 1000: REM *********RAINFALL IN GRAMS
60 INPUT "DEPTH OF BEDDING MATERIAL (MM)"; DEPTH
61 VOL = (BEDAREA * 10000) * (DEPTH / 10): REM ***********IN CM3
90 INTENSITY = RAINS / DURAT
100 PRINT "RAIN INTENSITY (MM/H)"; INTENSITY
REM ********************** BLOCK RETENTION CALCULATIONS FROM
HERE ************
REM *********CALCULATIONS BELOW ARE FOR SINGLE BLOCKS ONLY
********
BRET = (LOG(FR / 60) / LOG(10)) * 37.04 + 68.8
129 BRETT = (BRET * (BEDAREA / .02) * 1.16): REM BLOCK RETENTION IN
GRAMS WHOLE SURFACE
130 IF RAING < BRETT THEN BRETT = RAING * .85
135 BRETMM = ((BRETT / BEDAREA) / 1000): REM BLOCK RETENTION
WHOLE SURFACE
REM *********************************  GRAVEL RETENTION
CALCULATIONS FROM HERE
PRINT "TYPE OF SUBMATRIX (P)EA GRAVEL (L)IMESTONE"; : INPUT A$
140 IF A$ = "P" OR A$ = "P" THEN PRINT "PEA GRAVEL IS SELECTED "
150 IF A$ = "L" OR A$ = "L" THEN PRINT "LIMESTONE IS SELECTED"
160 IF A$ = "P" OR A$ = "P" THEN GOTO 200
170 IF A$ = "L" OR A$ = "L" THEN GOTO 352
REM *****************DATA INPUT FOR PEA GRAVEL CALCULATIONS
*****************
200 CLS
202 PRINT "PLEASE SELECT GRAIN SIZE OF BEDDING MATERIAL :"
203 PRINT : PRINT : PRINT
204 PRINT " 1 TO 10MM  (1)"
205 PRINT " 5 TO 10MM  (2)"
```

```
206 PRINT " 3 TO  5MM  (3)"
207 PRINT " 1 TO  3MM  (4)"
208 PRINT : PRINT
209 INPUT "ENTER YOUR SELECTION 1 TO 4 :"; A
210 IF A > 4 THEN GOTO 202
211 IF A > 1 THEN GOTO 336
336 IF A = 1 THEN GOTO 337
IF A = 2 THEN GOTO 340
IF A = 3 THEN GOTO 344
IF A = 4 THEN GOTO 348
REM *************** GRAVEL RETENTION CALCULATIONS FROM HERE
*****************
REM ********************SELECTION FOR 1 TO 10MM GRAIN
*************************
337 IF RAING < (((69.2 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 69.2)) +
BRETT) THEN WRET = (RAING - BRETT) ELSE GOTO 338
338 IF RAING > (((69.2 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 69.2)) +
BRETT) THEN WRET = 69.2 * (VOL / 1000) + (((.15 * BEDAREA) * 100) * 69.2)
339 GOTO 360
REM ********************SELECTION FOR 5 TO 10MM GRAIN
**********************
340 IF A > 2 THEN GOTO 344
341 IF RAING < (((45.59 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 45.59)) +
BRETT) THEN WRET = (RAING - BRETT) ELSE GOTO 342
342 IF RAING > (((45.59 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 45.59)) +
BRETT) THEN WRET = 45.59 * (VOL / 1000) + (((.15 * BEDAREA) * 100) * 45.59)
343 GOTO 360
REM ********************SELECTION FOR 3 TO 5MM GRAIN
************************
344 IF A > 3 THEN GOTO 348
345 IF RAING < (((101.39 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 101.39)) +
BRETT) THEN WRET = (RAING - BRETT) ELSE GOTO 346
346 IF RAING > (((101.39 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 101.39)) +
BRETT) THEN WRET = 101.39 * (VOL / 1000) + (((.15 * BEDAREA) * 100) *
101.39)
347 GOTO 360
REM ********************SELECTION FOR 1 TO 3MM
********************************
348 ON A > 4 GOTO 349
349 IF RAING < (((132.77 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 132.77)) +
BRETT) THEN WRET = (RAING - BRETT) ELSE GOTO 350
350 IF RAING > (((132.77 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 132.77)) +
BRETT) THEN WRET = 132.77 * (VOL / 1000) + (((.15 * BEDAREA) * 100) *
132.77)
351 GOTO 360
REM ********************SELECTION FOR LIMESTONE
***************************
```

```
352 CLS : PRINT : PRINT : PRINT
353 PRINT " 5 TO 10MM  (1)"
354 INPUT "PLEASE ENTER YOUR SELECTION "; A
355 IF A > 1 THEN 352
358 IF RAING < (((56.81 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 56.81)) +
BRETT) THEN WRET = (RAING - BRETT) ELSE GOTO 359
359 IF RAING > (((56.81 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 56.81)) +
BRETT) THEN WRET = 56.81 * (VOL / 1000) + (((.15 * BEDAREA) * 100) * 56.81)
360 WRETMM = ((WRET / BEDAREA) / 1000)
370 TOTR = BRETT + WRET: REM ****** TOTAL RETENTION IN GRAMS
380 TOTRMM = BRETMM + WRETMM: REM ***TOTAL RETENTION IN MM
CLS : REM *****************EVAPORATION CALCULATIONS FROM HERE
**********************
476 INPUT "LENGTH OF INTER-RAINFALL DRY PERIOD´(HOURS,MINS)=";
HIRP, MIRP:
477 IRP = MIRP + (HIRP * 60)

REM *****************BLOCK EVAPORATION CALCULATIONS
**************************
BEVAP = (LOG(IRP / 60) / LOG(10)) * 36.41 - 41.62
1000 BEVAPT = BEVAP * (BEDAREA / .02)

1002 REM *************GRAVEL EVAPORATION CALCULATIONS FROM
HERE ********************
1010 IF A$ = "L" OR A$ = "L" AND A = 1 THEN GOTO 2600
1020 IF A$ = "P" OR A$ = "P" THEN GOTO 1021
1021 IF A = 1 THEN GOTO 1110
1030 IF A = 2 THEN GOTO 1455
1040 IF A = 3 THEN GOTO 1800
1050 IF A = 4 THEN GOTO 2200
1100 REM ***********PEA GRAVEL SELECTION (1) CALCULATIONS 1-10MM
***************
1110 IF IRP > 0 AND IRP <= 60 THEN GOTO 1120 ELSE 1140
1120 GEVAP = ((.13 / 60) * IRP)
1140 IF IRP > 60 AND IRP <= 120 THEN GOTO 1150 ELSE 1170
1150 GEVAP = (((.04 / 60) * (IRP - 60)) + .13)
1170 IF IRP > 120 AND IRP <= 180 THEN GOTO 1180 ELSE 1200
1180 GEVAP = (((.09 / 60) * (IRP - 120)) + .17)
1200 IF IRP > 180 AND IRP <= 240 THEN GOTO 1210 ELSE 1230
1210 GEVAP = (((.08 / 60) * (IRP - 180)) + .26)
1230 IF IRP > 240 AND IRP <= 300 THEN GOTO 1240 ELSE 1260
1240 GEVAP = (((.07 / 60) * (IRP - 240)) + .34)
1260 IF IRP > 300 AND IRP <= 360 THEN GOTO 1270 ELSE 1290
1270 GEVAP = (((.06 / 60) * (IRP - 300)) + .41)
1290 IF IRP > 360 AND IRP <= 420 THEN GOTO 1300 ELSE 1320
1300 GEVAP = (((.05 / 60) * (IRP - 360)) + .47)
1320 IF IRP > 420 AND IRP <= 480 THEN GOTO 1330 ELSE 1350
```

```
1330 GEVAP = (((.045 / 60) * (IRP - 420)) + .52)
1350 IF IRP > 480 AND IRP <= 540 THEN GOTO 1360 ELSE 1380
1360 GEVAP = (((.04 / 60) * (IRP - 480)) + .565)
1380 IF IRP > 540 AND IRP <= 600 THEN GOTO 1390 ELSE 1410
1390 GEVAP = (((.3 / 60) * (IRP - 540)) + .605)
1410 IF IRP > 600 AND IRP <= 3720 THEN GOTO 1420 ELSE 1430
1420 GEVAP = (((.012 / 3120) * (IRP - 600)) + .635)
1430 IF IRP > 3720 THEN GOTO 1440
1440 GEVAP = (((.01 / 11280) * (IRP - 3720)) + .647)
1445 GOTO 3000
REM ***************PEA GRAVEL SELECTION (2) CALCULATIONS 5-10MM
**********
1455 IF IRP > 0 AND IRP <= 60 THEN GOTO 1470 ELSE 1490
1470 GEVAP = ((.19 / 60) * IRP)
1490 IF IRP > 60 AND IRP <= 120 THEN GOTO 1500 ELSE 1520
1500 GEVAP = (((.09 / 60) * (IRP - 60)) + .19)
1520 IF IRP > 120 AND IRP <= 180 THEN GOTO 1530 ELSE 1550
1530 GEVAP = (((.12 / 60) * (IRP - 120)) + .28)
1550 IF IRP > 180 AND IRP <= 240 THEN GOTO 1560 ELSE 1580
1560 GEVAP = (((.05 / 60) * (IRP - 180)) + .4)
1580 IF IRP > 240 AND IRP <= 300 THEN GOTO 1590 ELSE 1610
1590 GEVAP = (((.04 / 60) * (IRP - 240)) + .45)
1610 IF IRP > 300 AND IRP <= 360 THEN GOTO 1620 ELSE 1640
1620 GEVAP = (((.03 / 60) * (IRP - 300)) + .49)
1640 IF IRP > 360 AND IRP <= 420 THEN GOTO 1650 ELSE 1670
1650 GEVAP = (((.026 / 60) * (IRP - 360)) + .52)
1670 IF IRP > 420 AND IRP <= 480 THEN GOTO 1680 ELSE 1700
1680 GEVAP = (((.021 / 60) * (IRP - 420)) + .546)
1700 IF IRP > 480 AND IRP <= 540 THEN GOTO 1710 ELSE 1730
1710 GEVAP = (((.02 / 60) * (IRP - 480)) + .567)
1730 IF IRP > 540 AND IRP <= 600 THEN GOTO 1740 ELSE 1760
1740 GEVAP = (((.019 / 60) * (IRP - 540)) + .587)
1750 IF IRP > 600 AND IRP <= 3720 THEN GOTO 1755 ELSE 1760
1755 GEVAP = (((.01 / 3120) * (IRP - 600)) + .606)
1760 IF IRP > 3720 THEN GOTO 1765
1765 GEVAP = (((.01 / 11280) * (IRP - 3720)) + .787)
1780 GOTO 3000
REM ****************PEA GRAVEL SELECTION (3) CALCULATIONS 3-5MM
**********
1800 IF IRP > 0 AND IRP <= 60 THEN GOTO 1820 ELSE 1840
1820 GEVAP = ((.13 / 60) * IRP)
1840 IF IRP > 60 AND IRP <= 120 THEN GOTO 1850 ELSE 1870
1850 GEVAP = (((.08 / 60) * (IRP - 60)) + .13)
1870 IF IRP > 120 AND IRP <= 180 THEN GOTO 1880 ELSE 1900
1880 GEVAP = (((.16 / 60) * (IRP - 120)) + .21)
1900 IF IRP > 180 AND IRP <= 240 THEN GOTO 1910 ELSE 1930
1910 GEVAP = (((.07 / 60) * (IRP - 180)) + .37)
```

```
1930 IF IRP > 240 AND IRP <= 300 THEN GOTO 1940 ELSE 1960
1940 GEVAP = (((.06 / 60) * (IRP - 240)) + .44)
1960 IF IRP > 300 AND IRP <= 360 THEN GOTO 1970 ELSE 1990
1970 GEVAP = (((.05 / 60) * (IRP - 300)) + .5)
1990 IF IRP > 360 AND IRP <= 420 THEN GOTO 2000 ELSE 2020
2000 GEVAP = (((.04 / 60) * (IRP - 360)) + .55)
2020 IF IRP > 420 AND IRP <= 480 THEN GOTO 2030 ELSE 2050
2030 GEVAP = (((.03 / 60) * (IRP - 420)) + .59)
2050 IF IRP > 480 AND IRP <= 540 THEN GOTO 2060 ELSE 2080
2060 GEVAP = (((.025 / 60) * (IRP - 480)) + .62)
2080 IF IRP > 540 AND IRP <= 600 THEN GOTO 2090 ELSE 2110
2090 GEVAP = (((.02 / 60) * (IRP - 540)) + .645)
2100 IF IRP > 600 AND IRP <= 3720 THEN GOTO 2110 ELSE 2130
2110 GEVAP = (((.016 / 3120) * (IRP - 600)) + .665)
2130 IF IRP > 3720 THEN GOTO 2140
2140 GEVAP = (((.01 / 11280) * (IRP - 3720)) + .681)
2160 GOTO 3000
REM ****************PEA GRAVEL SELECTION (4) CALCULATIONS 1-3MM
************
2200 IF IRP > 0 AND IRP <= 60 THEN GOTO 2220 ELSE 2240
2220 GEVAP = ((.1 / 60) * IRP)
2240 IF IRP > 60 AND IRP <= 120 THEN GOTO 2250 ELSE 2270
2250 GEVAP = (((.1 / 60) * (IRP - 60)) + .21)
2270 IF IRP > 120 AND IRP <= 180 THEN GOTO 2280 ELSE 2300
2280 GEVAP = (((.14 / 60) * (IRP - 120)) + .42)
2300 IF IRP > 180 AND IRP <= 240 THEN GOTO 2310 ELSE 2330
2310 GEVAP = (((.08 / 60) * (IRP - 180)) + .58)
2330 IF IRP > 240 AND IRP <= 300 THEN GOTO 2340 ELSE 2360
2340 GEVAP = (((.07 / 60) * (IRP - 240)) + .68)
2360 IF IRP > 300 AND IRP <= 360 THEN GOTO 2370 ELSE 2390
2370 GEVAP = (((.06 / 60) * (IRP - 300)) + .75)
2390 IF IRP > 360 AND IRP <= 420 THEN GOTO 2400 ELSE 2420
2400 GEVAP = (((.04 / 60) * (IRP - 360)) + .81)
2420 IF IRP > 420 AND IRP <= 480 THEN GOTO 2430 ELSE 2450
2430 GEVAP = (((.03 / 60) * (IRP - 420)) + .86)
2450 IF IRP > 480 AND IRP <= 540 THEN GOTO 2460 ELSE 2480
2460 GEVAP = (((.025 / 60) * (IRP - 480)) + .89)
2480 IF IRP > 540 AND IRP <= 600 THEN GOTO 2490 ELSE 2510
2490 GEVAP = (((.024 / 60) * (IRP - 540)) + .92)
2500 IF IRP > 600 AND IRP <= 3720 THEN GOTO 2510 ELSE 2520
2510 GEVAP = (((.022 / 3120) * (IRP - 600)) + .945)
2520 IF IRP > 3720 GOTO 2530
2530 GEVAP = (((.01 / 11280) * (IRP - 3720)) + .965)
2550 GOTO 3000
2600 REM *****************LIMESTONE SELECTION (1) CALCULATIONS
*************
2610 IF IRP > 0 AND IRP <= 60 THEN GOTO 2620 ELSE 2640
```

```
2620 GEVAP = ((.15 / 60) * IRP)
2640 IF IRP > 60 AND IRP <= 120 THEN GOTO 2650 ELSE 2670
2650 GEVAP = (((.17 / 60) * (IRP - 60)) + .15)
2670 IF IRP > 120 AND IRP <= 180 THEN GOTO 2680 ELSE 2700
2680 GEVAP = (((.06 / 60) * (IRP - 120)) + .32)
2700 IF IRP > 180 AND IRP <= 240 THEN GOTO 2710 ELSE 2730
2710 GEVAP = (((.11 / 60) * (IRP - 180)) + .38)
2730 IF IRP > 240 AND IRP <= 300 THEN GOTO 2740 ELSE 2760
2740 GEVAP = (((.09 / 60) * (IRP - 240)) + .49)
2760 IF IRP > 300 AND IRP <= 360 THEN GOTO 2770 ELSE 2790
2770 GEVAP = (((.08 / 60) * (IRP - 300)) + .58)
2790 IF IRP > 360 AND IRP <= 420 THEN GOTO 2800 ELSE 2820
2800 GEVAP = (((.065 / 60) * (IRP - 360)) + .66)
2820 IF IRP > 420 AND IRP <= 480 THEN GOTO 2830 ELSE 2850
2830 GEVAP = (((.05 / 60) * (IRP - 420)) + .725)
2850 IF IRP > 480 AND IRP <= 540 THEN GOTO 2860 ELSE 2880
2860 GEVAP = (((.03 / 60) * (IRP - 480)) + .775)
2880 IF IRP > 540 AND IRP <= 600 THEN GOTO 2890 ELSE 2910
2890 GEVAP = (((.02 / 60) * (IRP - 540)) + .805)
2910 IF IRP > 600 AND IRP <= 3720 THEN GOTO 2920 ELSE 2930
2920 GEVAP = (((.012 / 3120) * (IRP - 600)) + .825)
2930 IF IRP > 3720 GOTO 2940
2940 GEVAP = (((.01 / 11280) * (IRP - 3720)) + .837)
2960 GOTO 3000
REM **** CALCULATIONS OF EVAPORATION FROM THE STRUCTURE AREA
********************
REM *************************** GRAVEL
EVAPORATION******************************
3000 GEVAPT = (((BEDAREA * 10000) * .15) / 8.55) * GEVAP
3002 GEVAPTMM = (GEVAPT / BEDAREA) / 1000
REM ************************** BLOCK EVAPORATION
******************************
3003 IF BEVAPT > ((WRET + BRETT) - GEVAPT) THEN BEVAPT = ((WRET +
BRETT) - GEVAPT)
3005 BEVAPTMM = (BEVAPT / BEDAREA) / 1000
3010 GRET1 = WRETMM - ((GEVAPT / BEDAREA) / 1000): REM **** WATER
RETAINED IN GRAVEL AFTER EVAPORATION
3020 BRET1 = BRETMM - BEVAPTMM
TOTEMM = GEVAPTMM + BEVAPTMM
DISMM = RAINS - TOTRMM
REM*****************************SECTION
TWO*************************************************
CLS : REM *****************INPUT DATA FOR THE NEXT RAINFALL
EVENTS***************
PRINT
"================================================================
==========="
```

```
PRINT "                    DATA INPUT SEQUENCE SECOND RAINFALL EVENT"
PRINT
"=================================================================
=========="
INPUT "ENTER DEPTH OF RAINFALL REACHING THE SURFACE IN EVENT 2
(MM)"; RAINS2
INPUT "DURATION OF RAINFALL EVENT (HOURS,MINS)= "; HOURS2, MINS2:
FR2 = MINS2 + (HOURS2 * 60): REM TIME CONVERTED TO MINUTES
DURAT2 = FR2 / 60
INTENSITY2 = (RAINS2 / (FR2 / 60))
RAING2 = (BEDAREA * RAINS2) * 1000: REM *********RAINFALL IN GRAMS
INPUT "LENGTH OF INTER-RAINFALL DRY PERIOD (HOURS,MINUTES)=";
HIRP2, MIRP2:
IRP2 = MIRP2 + (HIRP2 * 60): REM IRP2 CONVERTED INTO MINUTES
REM ********************** BLOCK RETENTION CALCULATIONS FROM
HERE ************
B1 = BRET - BEVAP
B2 = (B1 - 68.8) / 37.04
B3 = 10 ^ (B2)
BRET2 = (LOG((FR2 / 60) + B3) / LOG(10)) * 37.04 + 68.8
REM BLOCK RETENTION IN GRAMS WHOLE SURFACE
4129 BRETT2 = (BRET2 * (BEDAREA / .02) * 1.2952)
4130 IF RAING2 < BRETT2 THEN BRETT2 = RAING2 * .85
4135 BRETMM2 = ((BRETT2 / BEDAREA) / 1000)
REM MM BLOCK RETENTION FOR THE WHOLE SURFACE
REM *****************DATA INPUT FOR SECOND PEA GRAVEL
CALCULATIONS *****************
4200 IF A$ = "P" OR A$ = "P" AND A > 1 THEN GOTO 4230
4205 IF A$ = "L" OR A$ = "L" THEN GOTO 4350
REM ********************SELECTION FOR 1 TO 10MM GRAIN
*************************
4210 IF RAING2 < (((69.2 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 69.2) +
BRETT2) THEN WRET2 = (RAING2 - BRETT2) + GRET1 ELSE GOTO 4215
4215 IF RAING2 > (((69.2 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 69.2) +
BRETT2) THEN WRET2 = (69.2 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 69.2)
4212 IF WRET2 > (69.2 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 69.2) THEN
WRET2 = (69.2 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 69.2)
4220 GOTO 4400
REM ********************SELECTION FOR 5 TO 10MM GRAIN
**********************
4230 IF A > 2 THEN GOTO 4250
4235 IF RAING2 < (((45.59 * (VOL / 1000)) + ((.15 *
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BEDAREA) * 100) * 45.59) + BRETT2) THEN WRET2 = (RAING2 - BRETT2) +
GRET1 ELSE GOTO 4240
4240 IF RAING2 > (((45.59 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 45.59) +
BRETT2) THEN WRET2 = (45.59 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) *
45.59)
4242 IF WRET2 > (45.59 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 45.59)
THEN WRET2 = (45.59 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 45.59)
4245 GOTO 4400
REM ********************SELECTION FOR 3 TO 5MM GRAIN
************************
4250 IF A > 3 THEN GOTO 4270
4255 IF RAING2 < (((101.39 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 101.39) +
BRETT2) THEN WRET2 = (RAING2 - BRETT2) + GRET1 ELSE GOTO 4260
4260 IF RAING2 > (((101.39 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 101.39) +
BRETT2) THEN WRET2 = (101.39 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) *
101.39)
4262 IF WRET2 > (101.39 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 101.39)
THEN WRET2 = (101.39 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 101.39)
4265 GOTO 4400
REM ********************SELECTION FOR 1 TO 3MM
********************************
4270 ON A > 4 GOTO 4275
4275 IF RAING2 < (((132.77 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 132.77) +
BRETT2) THEN WRET2 = (RAING2 - BRETT2) + GRET1 ELSE GOTO 4280
4280 IF RAING2 > (((132.77 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 132.77) +
BRETT2) THEN WRET2 = (132.77 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) *
132.77)
4282 IF WRET2 > (132.77 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 132.77)
THEN WRET2 = (132.77 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 132.77)
4285 GOTO 4400
REM ********************SELECTION FOR LIMESTONE
****************************
4350 IF RAING2 < (((56.81 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 56.81) +
BRETT2) THEN WRET2 = (RAING2 - BRETT2) + GRET1 ELSE GOTO 4355
4355 IF RAING2 > (((56.81 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 56.81) +
BRETT2) THEN WRET2 = (56.81 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) *
56.81)
4356 IF WRET2 > (56.81 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 56.81)
THEN WRET2 = (56.81 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 56.81)
4400 WRETMM2 = ((WRET2 / BEDAREA) / 1000)
4420 TOTRMM2 = BRETMM2 + WRETMM2: REM ***TOTAL RETENTION IN
MM
REM ****************BLOCK EVAPORATION CALCULATIONS
*************************
BEVAP2 = (LOG(IRP2 / 60) / LOG(10)) * 36.41 - 41.62: REM PER BLOCK
BEVAPT2 = BEVAP2 * (BEDAREA / .02): REM WHOLE SURFACE
```

```
REM *************GRAVEL EVAPORATION CALCULATIONS FROM HERE
********************
5001 IF A$ = "L" OR A$ = "L" THEN GOTO 5650
5010 IF A$ = "P" OR A$ = "P" THEN GOTO 5021
5021 IF A = 1 THEN GOTO 5100
5030 IF A = 2 THEN GOTO 5225
5040 IF A = 3 THEN GOTO 5450
5050 IF A = 4 THEN GOTO 5580
5060 REM ***********PEA GRAVEL SELECTION (1) CALCULATIONS 1-10MM
***************
5100 IF IRP2 > 0 AND IRP2 <= 60 THEN GOTO 5105 ELSE 5110
5105 GEVAP2 = ((.13 / 60) * IRP2)
5110 IF IRP2 > 60 AND IRP2 <= 120 THEN GOTO 5115 ELSE 5120
5115 GEVAP2 = (((.04 / 60) * (IRP2 - 60)) + .13)
5120 IF IRP2 > 120 AND IRP2 <= 180 THEN GOTO 5125 ELSE 5130
5125 GEVAP2 = (((.09 / 60) * (IRP2 - 120)) + .17)
5130 IF IRP2 > 180 AND IRP2 <= 240 THEN GOTO 5135 ELSE 5140
5135 GEVAP2 = (((.08 / 60) * (IRP2 - 180)) + .26)
5140 IF IRP2 > 240 AND IRP2 <= 300 THEN GOTO 5145 ELSE 5150
5145 GEVAP2 = (((.07 / 60) * (IRP2 - 240)) + .34)
5150 IF IRP2 > 300 AND IRP2 <= 360 THEN GOTO 5155 ELSE 5160
5155 GEVAP2 = (((.06 / 60) * (IRP2 - 300)) + .41)
5160 IF IRP2 > 360 AND IRP2 <= 420 THEN GOTO 5165 ELSE 5170
5165 GEVAP2 = (((.05 / 60) * (IRP2 - 360)) + .47)
5170 IF IRP2 > 420 AND IRP2 <= 480 THEN GOTO 5175 ELSE 5180
5175 GEVAP2 = (((.045 / 60) * (IRP2 - 420)) + .52)
5180 IF IRP2 > 480 AND IRP2 <= 540 THEN GOTO 5185 ELSE 5190
5185 GEVAP2 = (((.04 / 60) * (IRP2 - 480)) + .565)
5190 IF IRP2 > 540 AND IRP2 <= 600 THEN GOTO 5195 ELSE 5200
5195 GEVAP2 = (((.3 / 60) * (IRP2 - 540)) + .605)
5200 IF IRP2 > 600 AND IRP2 <= 3720 THEN GOTO 5205 ELSE 5210
5205 GEVAP2 = (((.012 / 3120) * (IRP2 - 600)) + .635)
5210 IF IRP2 > 3720 THEN GOTO 5215
5215 GEVAP2 = (((.01 / 11280) * (IRP2 - 3720)) + .647)
5220 GOTO 5800
REM ***************PEA GRAVEL SELECTION (2) CALCULATIONS 5-10MM
**********
5225 IF IRP2 > 0 AND IRP2 <= 60 THEN GOTO 5230 ELSE 5235
5230 GEVAP2 = ((.19 / 60) * IRP2)
5235 IF IRP2 > 60 AND IRP2 <= 120 THEN GOTO 5240 ELSE 5245
5240 GEVAP2 = (((.09 / 60) * (IRP2 - 60)) + .19)
5245 IF IRP2 > 120 AND IRP2 <= 180 THEN GOTO 5250 ELSE 5255
5250 GEVAP2 = (((.12 / 60) * (IRP2 - 120)) + .28)
5255 IF IRP2 > 180 AND IRP2 <= 240 THEN GOTO 5260 ELSE 5265
5260 GEVAP2 = (((.05 / 60) * (IRP2 - 180)) + .4)
5265 IF IRP2 > 240 AND IRP2 <= 300 THEN GOTO 5270 ELSE 5275
5270 GEVAP2 = (((.04 / 60) * (IRP2 - 240)) + .45)
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5275 IF IRP2 > 300 AND IRP2 <= 360 THEN GOTO 5280 ELSE 5285
5280 GEVAP2 = (((.03 / 60) * (IRP2 - 300)) + .49)
5285 IF IRP2 > 360 AND IRP2 <= 420 THEN GOTO 5290 ELSE 5295
5290 GEVAP2 = (((.026 / 60) * (IRP2 - 360)) + .52)
5295 IF IRP2 > 420 AND IRP2 <= 480 THEN GOTO 5300 ELSE 5305
5300 GEVAP2 = (((.021 / 60) * (IRP2 - 420)) + .546)
5305 IF IRP2 > 480 AND IRP2 <= 540 THEN GOTO 5310 ELSE 5315
5310 GEVAP2 = (((.02 / 60) * (IRP2 - 480)) + .567)
5315 IF IRP2 > 540 AND IRP2 <= 600 THEN GOTO 5320 ELSE 5325
5320 GEVAP2 = (((.019 / 60) * (IRP2 - 540)) + .587)
5325 IF IRP2 > 600 AND IRP2 <= 3720 THEN GOTO 5330 ELSE 5335
5330 GEVAP2 = (((.01 / 3120) * (IRP2 - 600)) + .606)
5335 IF IRP2 > 3720 THEN GOTO 5340
5340 GEVAP2 = (((.01 / 11280) * (IRP2 - 3720)) + .787)
5445 GOTO 5800
REM ****************PEA GRAVEL SELECTION (3) CALCULATIONS 3-5MM
**********
5450 IF IRP2 > 0 AND IRP2 <= 60 THEN GOTO 5455 ELSE 5460
5455 GEVAP2 = ((.13 / 60) * IRP2)
5460 IF IRP2 > 60 AND IRP2 <= 120 THEN GOTO 5465 ELSE 5470
5465 GEVAP2 = (((.08 / 60) * (IRP2 - 60)) + .13)
5470 IF IRP2 > 120 AND IRP2 <= 180 THEN GOTO 5475 ELSE 5480
5475 GEVAP2 = (((.16 / 60) * (IRP2 - 120)) + .21)
5480 IF IRP2 > 180 AND IRP2 <= 240 THEN GOTO 5485 ELSE 5490
5485 GEVAP2 = (((.07 / 60) * (IRP2 - 180)) + .37)
5490 IF IRP2 > 240 AND IRP2 <= 300 THEN GOTO 5495 ELSE 5500
5495 GEVAP2 = (((.06 / 60) * (IRP2 - 240)) + .44)
5500 IF IRP2 > 300 AND IRP2 <= 360 THEN GOTO 5505 ELSE 5510
5505 GEVAP2 = (((.05 / 60) * (IRP2 - 300)) + .5)
5510 IF IRP2 > 360 AND IRP2 <= 420 THEN GOTO 5515 ELSE 5520
5515 GEVAP2 = (((.04 / 60) * (IRP2 - 360)) + .55)
5520 IF IRP2 > 420 AND IRP2 <= 480 THEN GOTO 5525 ELSE 5530
5525 GEVAP2 = (((.03 / 60) * (IRP2 - 420)) + .59)
5530 IF IRP2 > 480 AND IRP2 <= 540 THEN GOTO 5535 ELSE 5540
5535 GEVAP2 = (((.025 / 60) * (IRP2 - 480)) + .62)
5540 IF IRP2 > 540 AND IRP2 <= 600 THEN GOTO 5545 ELSE 5550
5545 GEVAP2 = (((.02 / 60) * (IRP2 - 540)) + .645)
5550 IF IRP2 > 600 AND IRP2 <= 3720 THEN GOTO 5555 ELSE 5560
5555 GEVAP2 = (((.016 / 3120) * (IRP2 - 600)) + .665)
5560 IF IRP2 > 3720 THEN GOTO 5565
5565 GEVAP2 = (((.01 / 11280) * (IRP2 - 3720)) + .681)
5570 GOTO 5800
REM ****************PEA GRAVEL SELECTION (4) CALCULATIONS 1-3MM
************
5580 IF IRP2 > 0 AND IRP2 <= 60 THEN GOTO 5585 ELSE 5590
5585 GEVAP2 = ((.1 / 60) * IRP2)
5590 IF IRP2 > 60 AND IRP2 <= 120 THEN GOTO 5595 ELSE 5600
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5595 GEVAP2 = (((.1 / 60) * (IRP2 - 60)) + .1)
5600 IF IRP2 > 120 AND IRP2 <= 180 THEN GOTO 5602 ELSE 5604
5602 GEVAP2 = (((.14 / 60) * (IRP2 - 120)) + .2)
5604 IF IRP2 > 180 AND IRP2 <= 240 THEN GOTO 5606 ELSE 5608
5606 GEVAP2 = (((.08 / 60) * (IRP2 - 180)) + .34)
5608 IF IRP2 > 240 AND IRP2 <= 300 THEN GOTO 5610 ELSE 5612
5610 GEVAP2 = (((.07 / 60) * (IRP2 - 240)) + .42)
5612 IF IRP2 > 300 AND IRP2 <= 360 THEN GOTO 5614 ELSE 5616
5614 GEVAP2 = (((.05 / 60) * (IRP2 - 300)) + .49)
5616 IF IRP2 > 360 AND IRP2 <= 420 THEN GOTO 5618 ELSE 5620
5618 GEVAP2 = (((.04 / 60) * (IRP2 - 360)) + .54)
5620 IF IRP2 > 420 AND IRP2 <= 480 THEN GOTO 5622 ELSE 5624
5622 GEVAP2 = (((.03 / 60) * (IRP2 - 420)) + .58)
5624 IF IRP2 > 480 AND IRP2 <= 540 THEN GOTO 5626 ELSE 5628
5626 GEVAP2 = (((.025 / 60) * (IRP2 - 480)) + .61)
5628 IF IRP2 > 540 AND IRP2 <= 600 THEN GOTO 5630 ELSE 5632
5630 GEVAP2 = (((.024 / 60) * (IRP2 - 540)) + .635)
5632 IF IRP2 > 600 AND IRP2 <= 3720 THEN GOTO 5634 ELSE 5636
5634 GEVAP2 = (((.022 / 3120) * (IRP2 - 600)) + .659)
5636 IF IRP2 > 3720 GOTO 5638
5638 GEVAP2 = (((.1 / 11280) * (IRP2 - 3720)) + .681)
5640 GOTO 5800
REM *****************LIMESTONE SELECTION (1) CALCULATIONS
*************
5650 IF IRP2 > 0 AND IRP2 <= 60 THEN GOTO 5660 ELSE 5670
5660 GEVAP2 = ((.15 / 60) * IRP2)
5670 IF IRP2 > 60 AND IRP2 <= 120 THEN GOTO 5680 ELSE 5690
5680 GEVAP2 = (((.17 / 60) * (IRP2 - 60)) + .15)
5690 IF IRP2 > 120 AND IRP2 <= 180 THEN GOTO 5700 ELSE 5705
5700 GEVAP2 = (((.06 / 60) * (IRP2 - 120)) + .32)
5705 IF IRP2 > 180 AND IRP2 <= 240 THEN GOTO 5710 ELSE 5715
5710 GEVAP2 = (((.11 / 60) * (IRP2 - 180)) + .38)
5715 IF IRP2 > 240 AND IRP2 <= 300 THEN GOTO 5720 ELSE 5725
5720 GEVAP2 = (((.09 / 60) * (IRP2 - 240)) + .49)
5725 IF IRP2 > 300 AND IRP2 <= 360 THEN GOTO 5730 ELSE 5735
5730 GEVAP2 = (((.08 / 60) * (IRP2 - 300)) + .58)
5735 IF IRP2 > 360 AND IRP2 <= 420 THEN GOTO 5740 ELSE 5745
5740 GEVAP2 = (((.065 / 60) * (IRP2 - 360)) + .66)
5745 IF IRP2 > 420 AND IRP2 <= 480 THEN GOTO 5750 ELSE 5755
5750 GEVAP2 = (((.05 / 60) * (IRP2 - 420)) + .725)
5755 IF IRP2 > 480 AND IRP2 <= 540 THEN GOTO 5760 ELSE 5765
5760 GEVAP2 = (((.03 / 60) * (IRP2 - 480)) + .775)
5765 IF IRP2 > 540 AND IRP2 <= 600 THEN GOTO 5770 ELSE 5775
5770 GEVAP2 = (((.02 / 60) * (IRP2 - 540)) + .805)
5775 IF IRP2 > 600 AND IRP2 <= 3720 THEN GOTO 5780 ELSE 5785
5780 GEVAP2 = (((.012 / 3120) * (IRP2 - 600)) + .825)
5785 IF IRP2 > 3720 GOTO 5790
```

```
5790 GEVAP2 = (((.01 / 11280) * (IRP2 - 3720)) + .837)
5795 GOTO 5800
5800 GEVAPT2 = (((BEDAREA * 10000) * .15) / 8.55) * GEVAP2
5810 GEVAPTMM2 = (GEVAPT2 / BEDAREA) / 1000
5820 IF BEVAPT2 > ((WRET2 + BRETT2) - GEVAPT2) THEN BEVAPT2 =
((WRET2 + BRETT2) - GEVAPT2)
5830 BEVAPTMM2 = (BEVAPT2 / BEDAREA) / 1000
5840 GRET2 = WRETMM2 - ((GEVAPT2 / BEDAREA) / 1000): REM **** WATER
RETAINED IN GRAVEL AFTER EVAPORATION
5850 BLOCKR = BRETMM2 - BEVAPTMM2
5890 TOTEVAPMM2 = BEVAPTMM2 + GEVAPTMM2
DISMM2 = RAINS2 - (TOTRMM2 - (GRET1 + BRET1)): DISL2 = DISMM2 *
BEDAREA
IF E = 2 THEN GOTO 12001
6000 PRINT
"====================================================================
================"
PRINT : PRINT " DATA INPUT SEQUENCE OF THIRD"
PRINT : PRINT
"====================================================================
=================="
6001 INPUT "ENTER DEPTH OF RAINFALL REACHING THE SURFACE IN
EVENT 3 (MM)"; RAINS3
INPUT "DURATION OF RAINFALL EVENT (HOURS,MINS)= "; HOURS3, MINS3:
FR3 = MINS3 + (HOURS3 * 60): REM TIME CONVERTED TO MINUTES
DURAT3 = FR3 / 60
INTENSITY3 = (RAINS3 / (FR3 / 60))
RAING3 = (BEDAREA * RAINS3) * 1000: REM *********RAINFALL IN GRAMS
INPUT "LENGTH OF INTER-RAINFALL DRY PERIOD (HOURS,MINUTES)=";
HIRP3, MIRP3:
IRP3 = MIRP3 + (HIRP3 * 60): REM IRP3 CONVERTED INTO MINUTES
REM ********************** BLOCK RETENTION CALCULATIONS FROM
HERE ************
Z1 = BRET2 - BEVAP2
Z2 = (Z1 - 68.8) / 37.04
Z3 = 10 ^ (Z2)
BRET3 = (LOG((FR3 / 60) + Z3) / LOG(10)) * 37.04 + 68.8
6129 BRETT3 = (BRET3 * (BEDAREA / .02) * 1.2588): REM BLOCK RETENTION
IN GRAMS WHOLE SURFACE
6130 IF RAING3 < BRETT3 THEN BRETT3 = RAING3 * .85
6135 BRETMM3 = ((BRETT3 / BEDAREA) / 1000)
REM *****************DATA INPUT FOR 3RD PEA GRAVEL CALCULATIONS
*****************
6200 IF A$ = "P" OR A$ = "P" AND A > 1 THEN GOTO 6230
6205 IF A$ = "L" OR A$ = "L" THEN GOTO 6350
REM *******************SELECTION FOR 1 TO 10MM GRAIN
*************************
```

```
6210 IF RAING3 < (((69.2 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 69.2) +
BRETT3) THEN WRET3 = (RAING3 - BRETT3) + GRET2 ELSE GOTO 6215
6215 IF RAING3 > (((69.2 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 69.2) +
BRETT3) THEN WRET3 = (69.2 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 69.2)
6212 IF WRET3 > (69.2 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 69.2) THEN
WRET3 = (69.2 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 69.2)
6220 GOTO 6400
REM ********************SELECTION FOR 5 TO 10MM GRAIN
***********************
6230 IF A > 2 THEN GOTO 6250
6235 IF RAING3 < (((45.59 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 45.59) +
BRETT3) THEN WRET3 = (RAING3 - BRETT3) + GRET2 ELSE GOTO 6240
6240 IF RAING3 > (((45.59 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 45.59) +
BRETT3) THEN WRET3 = (45.59 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) *
45.59)
6242 IF WRET3 > (45.59 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 45.59)
THEN WRET3 = (45.59 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 45.59)
6245 GOTO 6400
REM ********************SELECTION FOR 3 TO 5MM GRAIN
*************************
6250 IF A > 3 THEN GOTO 6270
6255 IF RAING3 < (((101.39 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 101.39) +
BRETT3) THEN WRET3 = (RAING3 - BRETT3) + GRET2 ELSE GOTO 6260
6260 IF RAING3 > (((101.39 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 101.39) +
BRETT3) THEN WRET3 = (101.39 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) *
101.39)
6262 IF WRET3 > (101.39 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 101.39)
THEN WRET3 = (101.39 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 101.39)
6265 GOTO 6400
REM ********************SELECTION FOR 1 TO 3MM
*********************************
6270 ON A > 4 GOTO 6275
6275 IF RAING3 < (((132.77 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 132.77) +
BRETT3) THEN WRET3 = (RAING3 - BRETT3) + GRET2 ELSE GOTO 6280
6280 IF RAING3 > (((132.77 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 132.77) +
BRETT3) THEN WRET3 = (132.77 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) *
132.77)
6282 IF WRET3 > (132.77 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 132.77)
THEN WRET3 = (132.77 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 132.77)
6285 GOTO 6400
REM ********************SELECTION FOR LIMESTONE
*****************************
6350 IF RAING3 < (((56.81 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 56.81) +
BRETT3) THEN WRET3 = (RAING3 - BRETT3) + GRET2 ELSE GOTO 6355
6355 IF RAING3 > (((56.81 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 56.81) +
BRETT3) THEN WRET3 = (56.81 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) *
56.81)
```

```
6356 IF WRET3 > (56.81 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 56.81)
THEN WRET3 = (56.81 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 56.81)
6400 WRETMM3 = ((WRET3 / BEDAREA) / 1000)
6420 TOTRMM3 = BRETMM3 + WRETMM3: REM ***TOTAL RETENTION IN
MM

REM *****************BLOCK EVAPORATION CALCULATIONS
***************************
BEVAP3 = (LOG(IRP3 / 60) / LOG(10)) * 36.41 - 41.62
7000 BEVAPT3 = BEVAP3 * (BEDAREA / .02)
REM *************GRAVEL EVAPORATION CALCULATIONS FROM HERE
********************
7001 IF A$ = "L" OR A$ = "L" THEN GOTO 7650
7010 IF A$ = "P" OR A$ = "P" THEN GOTO 7021
7021 IF A = 1 THEN GOTO 7100
7030 IF A = 2 THEN GOTO 7225
7040 IF A = 3 THEN GOTO 7450
7050 IF A = 4 THEN GOTO 7580
7060 REM ***********PEA GRAVEL SELECTION (1) CALCULATIONS 1-10MM
***************
7100 IF IRP3 > 0 AND IRP3 <= 60 THEN GOTO 7105 ELSE 7110
7105 GEVAP3 = ((.13 / 60) * IRP3)
7110 IF IRP3 > 60 AND IRP3 <= 120 THEN GOTO 7115 ELSE 7120
7115 GEVAP3 = (((.04 / 60) * (IRP3 - 60)) + .13)
7120 IF IRP3 > 120 AND IRP3 <= 180 THEN GOTO 7125 ELSE 7130
7125 GEVAP3 = (((.09 / 60) * (IRP3 - 120)) + .17)
7130 IF IRP3 > 180 AND IRP3 <= 240 THEN GOTO 7135 ELSE 7140
7135 GEVAP3 = (((.08 / 60) * (IRP3 - 180)) + .26)
7140 IF IRP3 > 240 AND IRP3 <= 300 THEN GOTO 7145 ELSE 7150
7145 GEVAP3 = (((.07 / 60) * (IRP3 - 240)) + .34)
7150 IF IRP3 > 300 AND IRP3 <= 360 THEN GOTO 7155 ELSE 7160
7155 GEVAP3 = (((.06 / 60) * (IRP3 - 300)) + .41)
7160 IF IRP3 > 360 AND IRP3 <= 420 THEN GOTO 7165 ELSE 7170
7165 GEVAP3 = (((.05 / 60) * (IRP3 - 360)) + .47)
7170 IF IRP3 > 420 AND IRP3 <= 480 THEN GOTO 7175 ELSE 7180
7175 GEVAP3 = (((.045 / 60) * (IRP3 - 420)) + .52)
7180 IF IRP3 > 480 AND IRP3 <= 540 THEN GOTO 7185 ELSE 7190
7185 GEVAP3 = (((.04 / 60) * (IRP3 - 480)) + .565)
7190 IF IRP3 > 540 AND IRP3 <= 600 THEN GOTO 7195 ELSE 7200
7195 GEVAP3 = (((.3 / 60) * (IRP3 - 540)) + .605)
7200 IF IRP3 > 600 AND IRP2 <= 3720 THEN GOTO 7205 ELSE 7210
7205 GEVAP3 = (((.012 / 3120) * (IRP3 - 600)) + .635)
7210 IF IRP3 > 3720 THEN GOTO 7215
7215 GEVAP3 = (((.01 / 11280) * (IRP3 - 3720)) + .647)
7220 GOTO 7800
REM **************PEA GRAVEL SELECTION (2) CALCULATIONS 5-10MM
**********
```

```
7225 IF IRP3 > 0 AND IRP3 <= 60 THEN GOTO 7230 ELSE 7235
7230 GEVAP3 = ((.19 / 60) * IRP3)
7235 IF IRP3 > 60 AND IRP3 <= 120 THEN GOTO 7240 ELSE 7245
7240 GEVAP3 = (((.09 / 60) * (IRP3 - 60)) + .19)
7245 IF IRP3 > 120 AND IRP3 <= 180 THEN GOTO 7250 ELSE 7255
7250 GEVAP3 = (((.12 / 60) * (IRP3 - 120)) + .28)
7255 IF IRP3 > 180 AND IRP3 <= 240 THEN GOTO 7260 ELSE 7265
7260 GEVAP3 = (((.05 / 60) * (IRP3 - 180)) + .4)
7265 IF IRP3 > 240 AND IRP3 <= 300 THEN GOTO 7270 ELSE 7275
7270 GEVAP3 = (((.04 / 60) * (IRP3 - 240)) + .45)
7275 IF IRP3 > 300 AND IRP3 <= 360 THEN GOTO 7280 ELSE 7285
7280 GEVAP3 = (((.03 / 60) * (IRP3 - 300)) + .49)
7285 IF IRP3 > 360 AND IRP3 <= 420 THEN GOTO 7290 ELSE 7295
7290 GEVAP3 = (((.026 / 60) * (IRP3 - 360)) + .52)
7295 IF IRP3 > 420 AND IRP3 <= 480 THEN GOTO 7300 ELSE 7305
7300 GEVAP3 = (((.021 / 60) * (IRP3 - 420)) + .546)
7305 IF IRP3 > 480 AND IRP3 <= 540 THEN GOTO 7310 ELSE 7315
7310 GEVAP3 = (((.02 / 60) * (IRP3 - 480)) + .567)
7315 IF IRP3 > 540 AND IRP3 <= 600 THEN GOTO 7320 ELSE 7325
7320 GEVAP3 = (((.019 / 60) * (IRP3 - 540)) + .587)
7325 IF IRP3 > 600 AND IRP3 <= 3720 THEN GOTO 7330 ELSE 7335
7330 GEVAP3 = (((.01 / 3120) * (IRP3 - 600)) + .606)
7335 IF IRP3 > 3720 THEN GOTO 7340
7340 GEVAP3 = (((.01 / 11280) * (IRP3 - 3720)) + .787)
7445 GOTO 7800
REM ****************PEA GRAVEL SELECTION (3) CALCULATIONS 3-5MM
**********
7450 IF IRP3 > 0 AND IRP3 <= 60 THEN GOTO 7455 ELSE 7460
7455 GEVAP3 = ((.13 / 60) * IRP3)
7460 IF IRP3 > 60 AND IRP3 <= 120 THEN GOTO 7465 ELSE 7470
7465 GEVAP3 = (((.08 / 60) * (IRP3 - 60)) + .13)
7470 IF IRP3 > 120 AND IRP3 <= 180 THEN GOTO 7475 ELSE 7480
7475 GEVAP3 = (((.16 / 60) * (IRP3 - 120)) + .21)
7480 IF IRP3 > 180 AND IRP3 <= 240 THEN GOTO 7485 ELSE 7490
7485 GEVAP3 = (((.07 / 60) * (IRP3 - 180)) + .37)
7490 IF IRP3 > 240 AND IRP3 <= 300 THEN GOTO 7495 ELSE 7500
7495 GEVAP3 = (((.06 / 60) * (IRP3 - 240)) + .44)
7500 IF IRP3 > 300 AND IRP3 <= 360 THEN GOTO 7505 ELSE 7510
7505 GEVAP3 = (((.05 / 60) * (IRP3 - 300)) + .5)
7510 IF IRP3 > 360 AND IRP3 <= 420 THEN GOTO 7515 ELSE 7520
7515 GEVAP3 = (((.04 / 60) * (IRP3 - 360)) + .55)
7520 IF IRP3 > 420 AND IRP3 <= 480 THEN GOTO 7525 ELSE 7530
7525 GEVAP3 = (((.03 / 60) * (IRP3 - 420)) + .59)
7530 IF IRP3 > 480 AND IRP3 <= 540 THEN GOTO 7535 ELSE 7540
7535 GEVAP3 = (((.025 / 60) * (IRP3 - 480)) + .62)
7540 IF IRP3 > 540 AND IRP3 <= 600 THEN GOTO 7545 ELSE 7550
7545 GEVAP3 = (((.02 / 60) * (IRP3 - 540)) + .645)
```

```
7550 IF IRP3 > 600 AND IRP3 <= 3720 THEN GOTO 7555 ELSE 7560
7555 GEVAP3 = (((.016 / 3120) * (IRP3 - 600)) + .665)
7560 IF IRP3 > 3720 THEN GOTO 7565
7565 GEVAP3 = (((.01 / 11280) * (IRP3 - 3720)) + .681)
7570 GOTO 7800
REM ****************PEA GRAVEL SELECTION (4) CALCULATIONS 1-3MM
************
7580 IF IRP3 > 0 AND IRP3 <= 60 THEN GOTO 7585 ELSE 7590
7585 GEVAP3 = ((.1 / 60) * IRP3)
7590 IF IRP3 > 60 AND IRP3 <= 120 THEN GOTO 7595 ELSE 7600
7595 GEVAP3 = (((.1 / 60) * (IRP3 - 60)) + .1)
7600 IF IRP3 > 120 AND IRP3 <= 180 THEN GOTO 7602 ELSE 7604
7602 GEVAP3 = (((.14 / 60) * (IRP3 - 120)) + .2)
7604 IF IRP3 > 180 AND IRP3 <= 240 THEN GOTO 7606 ELSE 7608
7606 GEVAP3 = (((.08 / 60) * (IRP3 - 180)) + .34)
7608 IF IRP3 > 240 AND IRP3 <= 300 THEN GOTO 7610 ELSE 7612
7610 GEVAP3 = (((.07 / 60) * (IRP3 - 240)) + .42)
7612 IF IRP3 > 300 AND IRP3 <= 360 THEN GOTO 7614 ELSE 7616
7614 GEVAP3 = (((.05 / 60) * (IRP3 - 300)) + .49)
7616 IF IRP3 > 360 AND IRP3 <= 420 THEN GOTO 7618 ELSE 7620
7618 GEVAP3 = (((.04 / 60) * (IRP3 - 360)) + .54)
7620 IF IRP3 > 420 AND IRP3 <= 480 THEN GOTO 7622 ELSE 7624
7622 GEVAP3 = (((.03 / 60) * (IRP3 - 420)) + .58)
7624 IF IRP3 > 480 AND IRP3 <= 540 THEN GOTO 7626 ELSE 7628
7626 GEVAP3 = (((.025 / 60) * (IRP3 - 480)) + .61)
7628 IF IRP3 > 540 AND IRP3 <= 600 THEN GOTO 7630 ELSE 7632
7630 GEVAP3 = (((.024 / 60) * (IRP3 - 540)) + .635)
7632 IF IRP3 > 600 AND IRP3 <= 3720 THEN GOTO 7634 ELSE 7636
7634 GEVAP3 = (((.022 / 3120) * (IRP3 - 600)) + .659)
7636 IF IRP3 > 3720 GOTO 7638
7638 GEVAP3 = (((.1 / 11280) * (IRP3 - 3720)) + .681)
7640 GOTO 7800
REM ******************LIMESTONE SELECTION (1) CALCULATIONS
*************
7650 IF IRP3 > 0 AND IRP3 <= 60 THEN GOTO 7660 ELSE 7670
7660 GEVAP3 = ((.15 / 60) * IRP3)
7670 IF IRP3 > 60 AND IRP3 <= 120 THEN GOTO 7680 ELSE 7690
7680 GEVAP3 = (((.17 / 60) * (IRP3 - 60)) + .15)
7690 IF IRP3 > 120 AND IRP3 <= 180 THEN GOTO 7700 ELSE 7705
7700 GEVAP3 = (((.06 / 60) * (IRP3 - 120)) + .32)
7705 IF IRP3 > 180 AND IRP3 <= 240 THEN GOTO 7710 ELSE 7715
7710 GEVAP3 = (((.11 / 60) * (IRP3 - 180)) + .38)
7715 IF IRP3 > 240 AND IRP3 <= 300 THEN GOTO 7720 ELSE 7725
7720 GEVAP3 = (((.09 / 60) * (IRP3 - 240)) + .49)
7725 IF IRP3 > 300 AND IRP3 <= 360 THEN GOTO 7730 ELSE 7735
7730 GEVAP3 = (((.08 / 60) * (IRP3 - 300)) + .58)
7735 IF IRP3 > 360 AND IRP3 <= 420 THEN GOTO 7740 ELSE 7745
```

```
7740 GEVAP3 = (((.065 / 60) * (IRP3 - 360)) + .66)
7745 IF IRP3 > 420 AND IRP3 <= 480 THEN GOTO 7750 ELSE 7755
7750 GEVAP3 = (((.05 / 60) * (IRP3 - 420)) + .725)
7755 IF IRP3 > 480 AND IRP3 <= 540 THEN GOTO 7760 ELSE 7765
7760 GEVAP3 = (((.03 / 60) * (IRP3 - 480)) + .775)
7765 IF IRP3 > 540 AND IRP3 <= 600 THEN GOTO 7770 ELSE 7775
7770 GEVAP3 = (((.02 / 60) * (IRP3 - 540)) + .805)
7775 IF IRP3 > 600 AND IRP3 <= 3720 THEN GOTO 7780 ELSE 7785
7780 GEVAP3 = (((.012 / 3120) * (IRP3 - 600)) + .825)
7785 IF IRP3 > 3720 GOTO 7790
7790 GEVAP3 = (((.01 / 11280) * (IRP3 - 3720)) + .837)
7795 GOTO 7800
REM ************************* GRAVEL
EVAPORATION*****************************
7800 GEVAPT3 = (((BEDAREA * 10000) * .15) / 8.55) * GEVAP3
7810 GEVAPTMM3 = (GEVAPT3 / BEDAREA) / 1000
REM ************************* BLOCK EVAPORATION
****************************
7820 IF BEVAPT3 > ((WRET3 + BRETT3) - GEVAPT3) THEN BEVAPT3 =
((WRET3 + BRETT3) - GEVAPT3)
7830 BEVAPTMM3 = (BEVAPT3 / BEDAREA) / 1000
7840 GRET3 = WRETMM3 - ((GEVAPT3 / BEDAREA) / 1000): REM **** WATER
RETAINED IN GRAVEL AFTER EVAPORATION
DISMM3 = RAINS3 - (TOTRMM3 - (GRET1 + BLOCKR)): DISL3 = DISMM3 *
BEDAREA
7890 TOTEVAPMM3 = BEVAPTMM3 + GEVAPTMM3
7892 IF E = 3 THEN GOTO 12001
12001
CLS
IF E = 1 THEN PRINT " VARIABLE                EVENT1 "
IF E = 2 THEN PRINT " VARIABLE                EVENT1          EVENT2 "
IF E = 3 THEN PRINT " VARIABLE                EVENT1          EVENT2
EVENT3"
PRINT "RAINFALL DURATION (HOURS)"
PRINT "RAINFALL INTENSITY (MM/H)"
PRINT "RAINFALL DEPTH (MM)"
PRINT "RAINFALL DISCHARGE (MM)"
PRINT "BLOCK RETENTION (MM)"
PRINT "GRAVEL RETENTION (MM)"
PRINT "TOTAL RETENTION (MM)"
PRINT "LENGTH OF DRY PERIOD (H,MIN)"
PRINT "BLOCK EVAPORATION (MM)"
PRINT "GRAVEL EVAPORATION (MM)"
PRINT "TOTAL EVAPORATION(MM)"
PRINT "BOX"; BOX
REM OUTPUT FOR RAINFALL EVENT 1
LOCATE 2, 31: PRINT USING "####.##"; FR / 60;
```

```
LOCATE 3, 31: PRINT USING "####.##"; INTENSITY
LOCATE 4, 31: PRINT USING "####.##"; RAINS
LOCATE 5, 31: PRINT USING "####.##"; DISMM
LOCATE 6, 31: PRINT USING "####.##"; BRETMM
LOCATE 7, 31: PRINT USING "####.##"; WRETMM
LOCATE 8, 31: PRINT USING "####.##"; TOTRMM
LOCATE 9, 31: PRINT USING "####.##"; IRP / 60;
LOCATE 10, 31: PRINT USING "####.##"; BEVAPTMM
LOCATE 11, 31: PRINT USING "####.###"; GEVAPTMM
LOCATE 12, 31: PRINT USING "####.##"; TOTEMM
REM OUTPUT FOR RAINFALL EVENT 2
LOCATE 2, 51: PRINT USING "####.##"; FR2 / 60;
LOCATE 3, 51: PRINT USING "####.##"; INTENSITY2
LOCATE 4, 51: PRINT USING "####.##"; RAINS2
LOCATE 5, 51: PRINT USING "####.##"; DISMM2
LOCATE 6, 51: PRINT USING "####.##"; BRETMM2
LOCATE 7, 51: PRINT USING "####.##"; WRETMM2
LOCATE 8, 51: PRINT USING "####.##"; TOTRMM2
LOCATE 9, 51: PRINT USING "####.##"; IRP2 / 60;
LOCATE 10, 51: PRINT USING "####.##"; BEVAPTMM2
LOCATE 11, 51: PRINT USING "####.###"; GEVAPTMM2
LOCATE 12, 51: PRINT USING "####.##"; TOTEVAPMM2
REM OUTPUT FOR RAINFALL EVENT 3
LOCATE 2, 71: PRINT USING "####.##"; FR3 / 60;
LOCATE 3, 71: PRINT USING "####.##"; INTENSITY3
LOCATE 4, 71: PRINT USING "####.##"; RAINS3
LOCATE 5, 71: PRINT USING "####.##"; DISMM3
LOCATE 6, 71: PRINT USING "####.##"; BRETMM3
LOCATE 7, 71: PRINT USING "####.##"; WRETMM3
LOCATE 8, 71: PRINT USING "####.##"; TOTRMM3
LOCATE 9, 71: PRINT USING "####.##"; IRP3 / 60;
LOCATE 10, 71: PRINT USING "####.##"; BEVAPTMM3
LOCATE 11, 71: PRINT USING "####.###"; GEVAPTMM3
LOCATE 12, 71: PRINT USING "####.##"; TOTEVAPMM3
END
```

REVISED PROGRAMME FOR CALCULATING THE HYDROLOGICAL PERFORMANCE OF THE MODEL CAR PARK SURFACE.

```
REM  PROGRAM CALLED REVMOD - REVISED MODEL
CLS
PRINT : PRINT : PRINT : PRINT : PRINT "  THIS PROGRAMME MODELS THE
RAINFALL, RETENTION AND DISCHARGE CHARACTERISTICS"
     PRINT :
     PRINT "           EXHIBITED BY A MODEL PERMEABLE PAVEMENT
STRUCTURE"
     PRINT : PRINT : PRINT : PRINT
     PRINT "                    COPYRIGHT TOFF BERRY 1995"
     PRINT : PRINT : PRINT : PRINT : PRINT : PRINT "                    PRESS
ANY KEY"

   COLOR 7, 0
   A$ = "?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?"
   WHILE INKEY$ <> "": WEND 'CLEAR KEYBOARD BUFFER

   WHILE INKEY$ = ""
     FOR A = 1 TO 5
       LOCATE 1, 1                   'PRINT HORIZONTAL SPARKLES
       PRINT MID$(A$, A, 80);
       LOCATE 22, 1
       PRINT MID$(A$, 6 - A, 80);

       FOR B = 2 TO 21               'PRINT VERTICAL SPARKLES
         C = (A + B) MOD 5
         IF C = 1 THEN
           LOCATE B, 80
           PRINT "!";
           LOCATE 23 - B, 1
           PRINT CHR$(173)
           ELSE
           LOCATE B, 80
           PRINT " ";
           LOCATE 23 - B, 1
           PRINT " ";
         END IF
       NEXT B
     NEXT A
   WEND
 REM***********************SECTION
 ONE************************************************
 1 CLS
```

```
2 PRINT
"==============================================================================
===============" 
3 PRINT "                    DATA INPUT SEQUENCE"
4 PRINT
"==============================================================================
===============" 
5 PRINT : PRINT : PRINT :
INPUT "BOX NUMBER"; BOX
INPUT "ENTER DEPTH OF RAINFALL REACHING SURFACE DURING EVENT 1
(MM)= "; RAINS
INPUT "DURATION OF RAINFALL EVENT (HOURS,MINS)= "; HOURS, MINS:
FR = MINS + (HOURS * 60): REM TIME CONVERTED TO MINUTES
DURAT = FR / 60
INTENSITY = (RAINS / (FR / 60))
INPUT "AREA OF SURFACE (M2)"; BEDAREA
RAING = (BEDAREA * RAINS) * 1000: REM *********RAINFALL IN GRAMS
INPUT "DEPTH OF BEDDING MATERIAL (MM)"; DEPTH
VOL = (BEDAREA * 10000) * (DEPTH / 10): REM ***********IN CM3
INTENSITY = RAINS / DURAT
REM ********************** BLOCK RETENTION CALCULATIONS FROM
HERE
REM *********CALCULATIONS BELOW ARE FOR SINGLE BLOCKS ONLY
BRET = (LOG(FR / 60) / LOG(10)) * 37.04 + 68.8
BRETT = ((BRET * (BEDAREA / .02)) * 1.29): REM BLOCK RETENTION GRAMS
WHOLE SURFACE
IF RAING < BRETT THEN BRETT = RAING * .85
BRETMM = ((BRETT / BEDAREA) / 1000): REM BLOCK RETENTION WHOLE
SURFACE
REM **  GRAVEL RETENTION CALCULATIONS FROM HERE
PRINT "TYPE OF SUBMATRIX (P)EA GRAVEL (L)IMESTONE"; : INPUT A$
IF A$ = "P" OR A$ = "P" THEN PRINT "PEA GRAVEL IS SELECTED "
IF A$ = "L" OR A$ = "L" THEN PRINT "LIMESTONE IS SELECTED"
IF A$ = "P" OR A$ = "P" THEN GOTO 200
IF A$ = "L" OR A$ = "L" THEN GOTO 352
REM *****************DATA INPUT FOR PEA GRAVEL CALCULATIONS
*****************
200 CLS
202 PRINT "PLEASE SELECT GRAIN SIZE OF BEDDING MATERIAL :"
203 PRINT : PRINT : PRINT
204 PRINT " 1 TO 10MM  (1)"
205 PRINT " 5 TO 10MM  (2)"
206 PRINT " 3 TO  5MM  (3)"
207 PRINT " 1 TO  3MM  (4)"
208 PRINT : PRINT
209 INPUT "ENTER YOUR SELECTION 1 TO 4 :"; A
210 IF A > 4 THEN GOTO 202
```

```
211 IF A > 1 THEN GOTO 336
336 IF A = 1 THEN GOTO 337
IF A = 2 THEN GOTO 340
IF A = 3 THEN GOTO 344
IF A = 4 THEN GOTO 348
REM **************** GRAVEL RETENTION CALCULATIONS FROM HERE
REM *********************SELECTION FOR 1 TO 10MM GRAIN
337 IF RAING < (((69.2 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 69.2)) +
BRETT) THEN WRET = (RAING - BRETT) ELSE GOTO 338
338 IF RAING > (((69.2 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 69.2)) +
BRETT) THEN WRET = 69.2 * (VOL / 1000) + (((.15 * BEDAREA) * 100) * 69.2)
339 GOTO 360
REM *********************SELECTION FOR 5 TO 10MM GRAIN
340 IF A > 2 THEN GOTO 344
341 IF RAING < (((45.59 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 45.59)) +
BRETT) THEN WRET = (RAING - BRETT) ELSE GOTO 342
342 IF RAING > (((45.59 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 45.59)) +
BRETT) THEN WRET = 45.59 * (VOL / 1000) + (((.15 * BEDAREA) * 100) * 45.59)
343 GOTO 360
REM *********************SELECTION FOR 3 TO 5MM GRAIN
344 IF A > 3 THEN GOTO 348
345 IF RAING < (((101.39 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 101.39)) +
BRETT) THEN WRET = (RAING - BRETT) ELSE GOTO 346
346 IF RAING > (((101.39 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 101.39)) +
BRETT) THEN WRET = 101.39 * (VOL / 1000) + (((.15 * BEDAREA) * 100) *
101.39)
347 GOTO 360
REM *********************SELECTION FOR 1 TO 3MM
348 ON A > 4 GOTO 349
349 IF RAING < (((132.77 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 132.77)) +
BRETT) THEN WRET = (RAING - BRETT) ELSE GOTO 350
350 IF RAING > (((132.77 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 132.77)) +
BRETT) THEN WRET = 132.77 * (VOL / 1000) + (((.15 * BEDAREA) * 100) *
132.77)
351 GOTO 360
REM *********************SELECTION FOR LIMESTONE
352 CLS : PRINT : PRINT : PRINT
353 PRINT " 5 TO 10MM  (1)"
354 INPUT "PLEASE ENTER YOUR SELECTION "; A
355 IF A > 1 THEN 352
358 IF RAING < (((56.81 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 56.81)) +
BRETT) THEN WRET = (RAING - BRETT) ELSE GOTO 359
359 IF RAING > (((56.81 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 56.81)) +
BRETT) THEN WRET = 56.81 * (VOL / 1000) + (((.15 * BEDAREA) * 100) * 56.81)
360 WRETMM = ((WRET / BEDAREA) / 1000)
380 TOTRMM = BRETMM + WRETMM: REM ***TOTAL RETENTION IN MM
PRINT "WRETMM"; WRETMM
```

```
CLS : REM *EVAPORATION CALCULATIONS FROM HERE
INPUT "LENGTH OF INTER-RAINFALL DRY PERIOD (HOURS,MINS)="; HIRP,
MIRP:
IRP = MIRP + (HIRP * 60)
TOTEMM = .04519 + (.27465 * TOTRMM) + (.002445 * (IRP / 60))
IF TOTEMM > TOTRMM THEN TOTEMM = TOTRMM
DIS = RAINS - TOTRMM
PRINT "TOT Q"; DIS
REM****************************SECTION
TWO************************************************

CLS : REM **INPUT DATA FOR THE NEXT RAINFALL EVENTS*
PRINT
"==================================================================
=========="
PRINT "                DATA INPUT SEQUENCE SECOND RAINFALL EVENT"
PRINT
"==================================================================
========="
INPUT "ENTER DEPTH OF RAINFALL REACHING THE SURFACE IN EVENT 2
(MM)"; RAINS2
INPUT "DURATION OF RAINFALL EVENT (HOURS,MINS)= "; HOURS2, MINS2:
FR2 = MINS2 + (HOURS2 * 60): REM TIME CONVERTED TO MINUTES
DURAT2 = FR2 / 60
INTENSITY2 = (RAINS2 / (FR2 / 60))
RAING2 = (BEDAREA * RAINS2) * 1000: REM *********RAINFALL IN GRAMS
INPUT "LENGTH OF INTER-RAINFALL DRY PERIOD (HOURS,MINUTES)=";
HIRP2, MIRP2:
IRP2 = MIRP2 + (HIRP2 * 60): REM IRP2 CONVERTED INTO MINUTES
REM ********************** BLOCK RETENTION CALCULATIONS FROM
HERE ************
B1 = BRET - (.85 * ((TOTEMM * 1000) * BEDAREA))
B2 = (B1 - 68.8) / 37.04
B3 = 10 ^ (B2)
BRET2 = (LOG((FR2 / 60) + B3) / LOG(10)) * 37.04 + 68.8
REM BLOCK RETENTION IN GRAMS WHOLE SURFACE
BRETT2 = ((BRET2 * (BEDAREA / .02)) * 1.29)
IF RAING2 < BRETT2 THEN BRETT2 = RAING2 * .85
BRETMM2 = ((BRETT2 / BEDAREA) / 1000)
REM MM BLOCK RETENTION FOR THE WHOLE SURFACE
REM ******************DATA INPUT FOR SECOND PEA GRAVEL
CALCULATIONS *****************
4200 IF A$ = "P" OR A$ = "P" AND A > 1 THEN GOTO 4230
4205 IF A$ = "L" OR A$ = "L" THEN GOTO 4350
REM *********************SELECTION FOR 1 TO 10MM GRAIN
*************************
```

```
4210 IF RAING2 < (((69.2 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 69.2) +
BRETT2) THEN WRET2 = (RAING2 - BRETT2) + GRET1 ELSE GOTO 4215
4215 IF RAING2 > (((69.2 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 69.2) +
BRETT2) THEN WRET2 = (69.2 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 69.2)
4212 IF WRET2 > (69.2 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 69.2) THEN
WRET2 = (69.2 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 69.2)
4220 GOTO 4400
REM ********************SELECTION FOR 5 TO 10MM GRAIN
**********************

4230 IF A > 2 THEN GOTO 4250
4235 IF RAING2 < (((45.59 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 45.59) +
BRETT2) THEN WRET2 = (RAING2 - BRETT2) + GRET1 ELSE GOTO 4240
4240 IF RAING2 > (((45.59 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 45.59) +
BRETT2) THEN WRET2 = (45.59 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) *
45.59)
4242 IF WRET2 > (45.59 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 45.59)
THEN WRET2 = (45.59 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 45.59)
4245 GOTO 4400
REM ********************SELECTION FOR 3 TO 5MM GRAIN
************************

4250 IF A > 3 THEN GOTO 4270
4255 IF RAING2 < (((101.39 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 101.39) +
BRETT2) THEN WRET2 = (RAING2 - BRETT2) + GRET1 ELSE GOTO 4260
4260 IF RAING2 > (((101.39 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 101.39) +
BRETT2) THEN WRET2 = (101.39 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) *
101.39)
4262 IF WRET2 > (101.39 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 101.39)
THEN WRET2 = (101.39 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 101.39)
4265 GOTO 4400
REM ********************SELECTION FOR 1 TO 3MM
*********************************

4270 ON A > 4 GOTO 4275
4275 IF RAING2 < (((132.77 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 132.77) +
BRETT2) THEN WRET2 = (RAING2 - BRETT2) + GRET1 ELSE GOTO 4280
4280 IF RAING2 > (((132.77 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 132.77) +
BRETT2) THEN WRET2 = (132.77 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) *
132.77)
4282 IF WRET2 > (132.77 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 132.77)
THEN WRET2 = (132.77 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 132.77)
4285 GOTO 4400
REM ********************SELECTION FOR LIMESTONE
****************************

4350 IF RAING2 < (((56.81 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 56.81) +
BRETT2) THEN WRET2 = (RAING2 - BRETT2) + GRET1 ELSE GOTO 4355
4355 IF RAING2 > (((56.81 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 56.81) +
BRETT2) THEN WRET2 = (56.81 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) *
56.81)
```

```
4356 IF WRET2 > (56.81 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 56.81)
THEN WRET2 = (56.81 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 56.81)
4400 WRETMM2 = ((WRET2 / BEDAREA) / 1000)
4420 TOTRMM2 = BRETMM2 + WRETMM2: REM ***TOTAL RETENTION IN
MM
TOTEVAPMM2 = .04519 + (.27465 * TOTRMM2) + (.002445 * (IRP2 / 60))
IF TOTEVAPMM2 > TOTRMM2 THEN TOTEVAPMM2 = TOTRMM2
DIS2 = RAINS2 - (TOTRMM2 - (TOTRMM - TOTEMM))
6000 PRINT
"==============================================================
================"
PRINT : PRINT " DATA INPUT SEQUENCE OF THIRD"
PRINT : PRINT
"==============================================================
=================="
6001 INPUT "ENTER DEPTH OF RAINFALL REACHING THE SURFACE IN
EVENT 3 (MM)"; RAINS3
INPUT "DURATION OF RAINFALL EVENT (HOURS,MINS)= "; HOURS3, MINS3:
FR3 = MINS3 + (HOURS3 * 60): REM TIME CONVERTED TO MINUTES
DURAT3 = FR3 / 60
INTENSITY3 = (RAINS3 / (FR3 / 60))
RAING3 = (BEDAREA * RAINS3) * 1000: REM *********RAINFALL IN GRAMS
INPUT "LENGTH OF INTER-RAINFALL DRY PERIOD (HOURS,MINUTES)=";
HIRP3, MIRP3:
IRP3 = MIRP3 + (HIRP3 * 60): REM IRP3 CONVERTED INTO MINUTES
REM ********************** BLOCK RETENTION CALCULATIONS FROM
HERE ************
Z1 = BRET2 - (.85 * ((TOTEVAPMM * 1000) * BEDAREA))
Z2 = (Z1 - 68.8) / 37.04
Z3 = 10 ^ (Z2)
BRET3 = (LOG((FR3 / 60) + Z3) / LOG(10)) * 37.04 + 68.8
6129 BRETT3 = ((BRET3 * (BEDAREA / .02)) * 1.29): REM BLOCK RETENTION
IN GRAMS WHOLE SURFACE
6130 IF RAING3 < BRETT3 THEN BRETT3 = RAING3 * .85
6135 BRETMM3 = ((BRETT3 / BEDAREA) / 1000)
REM *****************DATA INPUT FOR 3RD PEA GRAVEL CALCULATIONS
*****************
6200 IF A$ = "P" OR A$ = "P" AND A > 1 THEN GOTO 6230
6205 IF A$ = "L" OR A$ = "L" THEN GOTO 6350
REM ********************SELECTION FOR 1 TO 10MM GRAIN
*************************
6210 IF RAING3 < (((69.2 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 69.2) +
BRETT3) THEN WRET3 = (RAING3 - BRETT3) + GRET2 ELSE GOTO 6215
6215 IF RAING3 > (((69.2 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 69.2) +
BRETT3) THEN WRET3 = (69.2 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 69.2)
6212 IF WRET3 > (69.2 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 69.2) THEN
WRET3 = (69.2 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 69.2)
```

```
6220 GOTO 6400
REM *********************SELECTION FOR 5 TO 10MM GRAIN
************************
6230 IF A > 2 THEN GOTO 6250
6235 IF RAING3 < (((45.59 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 45.59) +
BRETT3) THEN WRET3 = (RAING3 - BRETT3) + GRET2 ELSE GOTO 6240
6240 IF RAING3 > (((45.59 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 45.59) +
BRETT3) THEN WRET3 = (45.59 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) *
45.59)
6242 IF WRET3 > (45.59 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 45.59)
THEN WRET3 = (45.59 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 45.59)
6245 GOTO 6400
REM *********************SELECTION FOR 3 TO 5MM GRAIN
*************************
6250 IF A > 3 THEN GOTO 6270
6255 IF RAING3 < (((101.39 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 101.39) +
BRETT3) THEN WRET3 = (RAING3 - BRETT3) + GRET2 ELSE GOTO 6260
6260 IF RAING3 > (((101.39 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 101.39) +
BRETT3) THEN WRET3 = (101.39 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) *
101.39)
6262 IF WRET3 > (101.39 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 101.39)
THEN WRET3 = (101.39 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 101.39)
6265 GOTO 6400
REM *********************SELECTION FOR 1 TO 3MM
*********************************
6270 ON A > 4 GOTO 6275
6275 IF RAING3 < (((132.77 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 132.77) +
BRETT3) THEN WRET3 = (RAING3 - BRETT3) + GRET2 ELSE GOTO 6280
6280 IF RAING3 > (((132.77 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 132.77) +
BRETT3) THEN WRET3 = (132.77 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) *
132.77)
6282 IF WRET3 > (132.77 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 132.77)
THEN WRET3 = (132.77 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 132.77)
6285 GOTO 6400
REM *********************SELECTION FOR LIMESTONE
****************************
6350 IF RAING3 < (((56.81 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 56.81) +
BRETT3) THEN WRET3 = (RAING3 - BRETT3) + GRET2 ELSE GOTO 6355
6355 IF RAING3 > (((56.81 * (VOL / 1000)) + ((.15 * BEDAREA) * 100) * 56.81) +
BRETT3) THEN WRET3 = (56.81 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) *
56.81)
6356 IF WRET3 > (56.81 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 56.81)
THEN WRET3 = (56.81 * (VOL / 1000)) + (((.15 * BEDAREA) * 100) * 56.81)
6400 WRETMM3 = ((WRET3 / BEDAREA) / 1000)
6420 TOTRMM3 = BRETMM3 + WRETMM3: REM ***TOTAL RETENTION IN
MM
DISMM3 = RAINS3 - (TOTRMM3 - (TOTRMM2 - TOTEVAPMM2)):
```

```
7890 TOTEVAPMM3 = .04519 + (.27465 * TOTRMM3) + (.002445 * (IRP / 60))
CLS
PRINT
PRINT "RAINFALL DURATION (HOURS)"
PRINT "RAINFALL INTENSITY (MM/H)"
PRINT "RAINFALL DEPTH (MM)"
PRINT "RAINFALL DISCHARGE (MM)"
PRINT "BLOCK RETENTION (MM)"
PRINT "GRAVEL RETENTION (MM)"
PRINT "TOTAL RETENTION (MM)"
PRINT "LENGTH OF DRY PERIOD (H,MIN)"
PRINT "TOTAL EVAPORATION(MM)"
REM OUTPUT FOR RAINFALL EVENT 1
LOCATE 2, 31: PRINT USING "####.##"; FR / 60;
LOCATE 3, 31: PRINT USING "####.##"; INTENSITY
LOCATE 4, 31: PRINT USING "####.##"; RAINS
LOCATE 5, 31: PRINT USING "####.##"; DIS
LOCATE 6, 31: PRINT USING "####.##"; BRETMM
LOCATE 7, 31: PRINT USING "####.##"; WRETMM
LOCATE 8, 31: PRINT USING "####.##"; TOTRMM
LOCATE 9, 31: PRINT USING "####.##"; IRP / 60;
LOCATE 10, 31: PRINT USING "####.##"; TOTEMM
REM OUTPUT FOR RAINFALL EVENT 2
LOCATE 2, 51: PRINT USING "####.##"; FR2 / 60;
LOCATE 3, 51: PRINT USING "####.##"; INTENSITY2
LOCATE 4, 51: PRINT USING "####.##"; RAINS2
LOCATE 5, 51: PRINT USING "####.##"; DIS2
LOCATE 6, 51: PRINT USING "####.##"; BRETMM2
LOCATE 7, 51: PRINT USING "####.##"; WRETMM2
LOCATE 8, 51: PRINT USING "####.##"; TOTRMM2
LOCATE 9, 51: PRINT USING "####.##"; IRP2 / 60;
LOCATE 10, 51: PRINT USING "####.##"; TOTEVAPMM2
REM OUTPUT FOR RAINFALL EVENT 3
LOCATE 2, 71: PRINT USING "####.##"; FR3 / 60;
LOCATE 3, 71: PRINT USING "####.##"; INTENSITY3
LOCATE 4, 71: PRINT USING "####.##"; RAINS3
LOCATE 5, 71: PRINT USING "####.##"; DISMM3
LOCATE 6, 71: PRINT USING "####.##"; BRETMM3
LOCATE 7, 71: PRINT USING "####.##"; WRETMM3
LOCATE 8, 71: PRINT USING "####.##"; TOTRMM3
LOCATE 9, 71: PRINT USING "####.##"; IRP3 / 60;
LOCATE 10, 71: PRINT USING "####.##"; TOTEVAPMM3
END
```